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A review of the combined effects of climate change and other local human stressors on the marine environment

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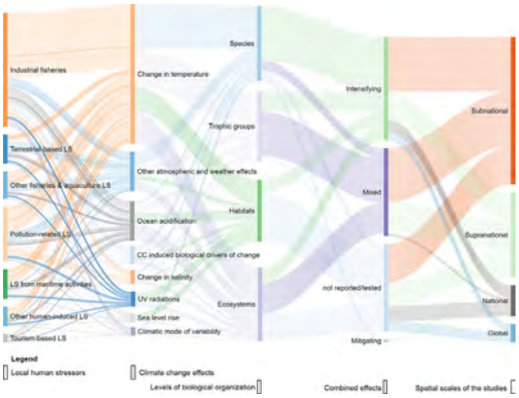
HIGHLIGHTS

- Local human stressors (LS) and climate change (CC) interact in marine environment.
- We review how cumulative effect assessments (CEA) address CC & LS combined effects.
- 52 LS & 27 CC stressors explored at different levels of biological diversity.
- CC-LS combined effects are context-dependent and vary among and within ecosystems.
- Urgency for CEAs to capture LS local effects that can exacerbate CC, to mitigate it.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change (CC) is a key, global driver of change of marine ecosystems. At local and regional scales, other local human stressors (LS) can interact with CC and modify its effects on marine ecosystems. Understanding the response of the marine environment to the combined effects of CC and LS is crucial to inform marine ecosystem-based management and planning, yet our knowledge of the potential effects of such interactions is fragmented.

At a global scale, we explored how cumulative effect assessments (CEAs) have addressed CC in the marine realm and discuss progress and shortcomings of current approaches. For this we conducted a systematic review on how

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CEAs investigated at different levels of biological organization ecological responses, functional aspects, and the combined effect of CC and HS.

Globally, the effects of 52 LS and of 27 CC-related stressors on the marine environment have been studied in combination, such as industrial fisheries with change in temperature, or sea level rise with artisanal fisheries, marine litter, change in sediment load and introduced alien species. CC generally intensified the effects of LS at species level. At trophic groups and ecosystem levels, the effects of CC either intensified or mitigated the effects of other HS depending on the trophic groups or the environmental conditions involved, thus suggesting that the combined effects of CC and LS are context-dependent and vary among and within ecosystems. Our results highlight that large-scale assessments on the spatial interaction and combined effects of CC and LS remain limited. More importantly, our results strengthen the urgent need of CEAs to capture local-scale effects of stressors that can exacerbate climate-induced changes. Ultimately, this will allow identifying management measures that aid counteracting CC effects at relevant scales.

Contents

1. Introduction

The global process of climate change (CC) is considered as a key driver of change for marine ecosystems affecting their resilience, functionality, and associated ecosystem services (Doney et al., 2012; Smale et al., 2019). Climate change is manifested by ocean warming and acidification, sea level rise, and the intensification of extreme weather events (e.g., storms), all impacting marine biodiversity dynamics at multiple temporal and spatial scales, from genes to ecosystems (IPCC, 2019). At the same time, more than 95% of the world's oceans are currently exposed to numerous other local stressors that result from different human activities (Halpern et al., 2008, 2015). Even though it is widely acknowledged that understanding the response of the marine environment to the combined effects of CC and local human stressors (LS) is crucial to ecosystem-based management, it is still a very difficult task due to the complexity of the interactions among CC, LS and the ecosystem components (Jutterström et al., 2014; Niiranen et al., 2013). Spatially explicit ecosystem-based management, together with the scientific knowledge of the effects of these interactions, should suggest counter actions and mitigation strategies (Gissi et al., 2019; Rilov et al., 2020).

Cumulative effects assessments (CEAs) are holistic evaluations of the combined effects of LS and natural processes on the environment (Jones, 2016). Hence, CEAs are an increasingly applied framework (Korpinen and Andersen, 2016; Stelzenmüller et al., 2020) that integrates information on multiple stressors and their interactions in order to estimate the cumulative expected impacts upon selected biotic components in marine and coastal regions worldwide (Foley et al., 2017; Jones, 2016; Korpinen et al., 2020; Stelzenmüller et al., 2018). The quality of CEA largely depends on the information used to understand the effects of interactions among different stressors, as well as on how impacts, baselines, scales, and significance are defined (Foley et al., 2017). Stressors' impacts on marine biodiversity may be nonlinear functions of stressors' intensities, and include direct and indirect feedbacks (Fu et al., 2018; Jutterström et al., 2014), whose information is often acquired through experiments or extensive field surveys (e.g., Bevilacqua et al., 2018; Crain et al., 2008; Ramírez et al., 2018). Knowledge on the vulnerability of targeted marine components at different levels of biological organization (e.g., ecosystem, trophic groups, habitat, species) to multiple stressors should be linked to spatially explicit current and projected levels of exposure at different spatial scales (Stelzenmüller et al., 2018) in order to transfer these relevant inputs into management recommendations.

Following the need to delineate and quantify the way CC and LS may act together in affecting the marine environment, potential pathways of interactions and impacts upon species, communities and/or ecosystems at various spatial scales have been investigated (Bartolino et al., 2014). For example, the combined effect of climate-induced coral bleaching and reduced calcification, with increasing pollution, nutrients and sediment input, have reduced the capacity of coral reefs to recover from disturbances (Bruno et al., 2007). Similarly, the adverse effects of intensive industrial fishing on top predators can be exacerbated by CC effects, together affecting their reproduction success (Ainley and Blight, 2009). Thus, due to the fact that climate-induced drivers of change pose continuous and dynamic threats to marine ecosystems at multiple levels of biological organization, they should be considered an essential part in CEAs of the marine environment (Rilov et al., 2020).

Recent reviews on CEAs provided syntheses of evidence and identified challenges and gaps in the framework (e.g., Halpern and Fujita, 2013; Hodgson et al., 2019), but mostly focused on the general methodological approaches (Korpinen and Andersen, 2016), the way methodological approaches address ecological complexity (Hodgson and Halpern, 2019), or their practical implementation in specific case study areas (Foley et al., 2017; Stelzenmüller et al., 2020). Here, we conducted a systematic literature review to distill emergent patterns in the understanding of combined effects of CC and different LS on ecological responses and functional aspects of marine environments, to understand the outcomes of these interactions and support decision processes within an ecosystem-based management framework. For each case, we considered the interactions and consequences of these effects on the investigated response variables, and the methodology employed to assess them (the research questions to guide our review are reported in Table 1). Furthermore, we evaluated the temporal and spatial scales considered. Finally, we discuss the main gaps in present knowledge and the challenges for future research and concrete applications.

2. Review approach and theoretical baselines

The studies were selected through a systematic literature review in Scopus and Web of Science, using a combination of keywords (following Hoegh-Guldberg and Bruno, 2010) (Table A.1). Our search (at 16/06/2020) resulted in 2043 studies (articles and reviews), which were further screened to determine their applicability to the objectives of the study. We excluded studies that: i) were not strictly related to the marine environment (e.g., terrestrial studies, or studies on transitional environments); ii) did not address any biological response variable (e.g., studies on climatology, geophysics, oceanography, or meteorology); or iii) did not include LS besides climate-induced drivers of change. Although we acknowledge that laboratory experiments in aquaria or mesocosms play a crucial role in addressing a range of theoretical and applied scientific questions, included those related to the effects of CC, issues relative to experimental scale and extrapolation of the results to real natural environment still hold (for a review see Petersen and Kemp, 2019). As our interest was to identify and appraise the current state of approaches exploring the combined effects of CC and LS in natural conditions at scales at which policy targets are designed and effective management could be implemented, we excluded that kind of experimental studies. This screening process led to a total of 107 eligible studies (Table A.2).

Following the rationale of Hodgson and Halpern (2019), the studies were grouped into four categories according to the level of biological organization they were referring to (i.e., species, trophic groups, habitats, and ecosystems, Table 2).

In order to elucidate spatial patterns and biases in the number of studies undertaken at a global scale, we grouped them according to the marine biogeographic realms and provinces classification sensu Spalding et al. (2007). We classified the methods used to assess the effects of CC in combination with LS according to Stelzenmüller et al. (2018) (Table A.3).

We recorded the LS considered in the reviewed studies (Table A.4). We depicted LS of two types (following Stelzenmüller et al., 2018): potential drivers of change (human activities such as fishery, shipping, mining), or pressures (such as pollution, human-induced introduction of alien species, change in predator density). We codified the LS into 52 classes, grouped into seven general categories for easier interpretation of the results, as follows: i) industrial fisheries, ii) other fishery and aquaculture-related LS, iii) pollution-related LS, iv) LS from maritime activities, v) terrestrial-based LS, vi) tourism-based LS, and vii) other LS (Table A.4). The seven categories were referred to the different human activities inducing LS, when possible, to highlight the relevance to management and planning.

CC effects were initially codified in 27 classes according to the variables, parameters or models adopted in the studies. Given the heterogeneity of the results from the literature research, to facilitate the analysis we grouped the 27 CC effects classes into eight broader categories: i) UV radiation, ii) ocean acidification, iii) sea level rise, iv) change in salinity,

Table 1
Objectives and related research questions addressed by our systematic literature review. CC = climate change, LS = local stressors.

Objectives	Research questions
1) Assessing the state of knowledge on multiple effects of combined CC and LS globally	1.1) At which level of biological organization have combined effects been studied and where? 1.2) Which methods have been used to study multiple effects including CC? 1.3) Which combined effects between CC and LS have been studied? (descriptive on LS, and CC variables) 1.4) At what spatial scales have multiple effects been studied? 1.5) What temporal scale has been adopted in the studies? (anticipatory or explanatory, according to Bonebrake et al., 2018)
2) Assessing the outcomes of the interactions among CC and LS	2.1) Do the studies report an effect of CC on top of LS? 2.2) If yes, do the studies report intensifying, mitigating, neutral, or mixed effects on the response variable?* 2.3) Are there any possible patterns to distill from the analysis of cause-effect relationships on the combined effect of CC and LS?

* The meaning of intensifying, mitigating, neutral, or mixed effects is explained in Fig. 1.

Table 2
Definition of the level of biological diversity (ecological foci) at which the combined effects of the global process of climate change (CC) and local human stressors (LS) were addressed by the studies (revised after Hodgson and Halpern, 2019).

Level of biological diversity	Description
Species	Research focuses on overall population size (biomass or abundance), or on a particular life stage of interest, such as adults, in response to a combination of CC and LS.
Trophic groups	Research focuses on the combined effects of CC and LS on interacting populations, e.g. trophic groups within food webs.
Habitats	Various ways exist to define habitats: individual species that represent an important type of habitat (e.g., seagrass), a complex of species that represent a habitat type (e.g., corals), or even a complex of abiotic and biotic habitats (e.g., hard shelf, or soft slope, seamount (Halpern et al., 2009, 2008)). In the first circumstance, habitats may be thought of as similar to populations, since the focus is on a single species and they may be used as indicators (Canter and Atkinson, 2011). Similarly, the output metric could be biomass, abundance or spatial coverage of the habitat type in response to different environmental conditions. In the second and third case, when the habitat represents a complex of different species, or an abiotic habitat, the most common metric is spatial coverage. The mapping approach is the method most frequently used for habitat assessment, and in some circumstances has been developed specifically to understand impacts on habitats (Ban et al., 2010; Halpern et al., 2009).
Ecosystems	Research focuses on both habitats and communities. Studies whose final outputs may focus on changes in abundance of key/representative species or ecosystem indicators intended to represent ecosystem responses to change (Butchart et al., 2010). Indicators are varied and may include measurements of biodiversity, community composition, total harvest, and ecosystem production (Samhouri et al., 2009).

v) change in temperature, vi) climatic mode of variability, vii) other atmospheric and weather effects, and viii) CC-induced biological drivers of change (Table A.5).

Then, we identified the related ecological response/s of the targeted features and classified the combined effects between CC and LS. Frequently adopted definitions of stressors interactions refer to additive, synergistic, and antagonistic effects according to Crain et al. (2008) and Folt et al. (1999). These definitions were then criticized and better specified (e.g., Brook et al., 2008; Côté et al., 2016; Piggott et al., 2015). Since the studies we reviewed did not often distinguish between "additive" and "synergistic" effects, and the existing terminology was often used inconsistently (Boyd et al., 2018; Côté et al., 2016; Piggott et al., 2015), we propose a simplified classification of the combined effects between LS and CC (Fig. 1), to overcome several pitfalls found among definitions (Côté et al., 2016). Following Piggott et al. (2015), we used the effects of independent stressors to delineate the boundaries between intensifying effects (i.e. combined effect exceeding independent effects, commonly referred in the literature as additive or synergistic) and mitigating effects (i.e. combined effect attenuated than independent effects, commonly referred in the literature as an antagonistic or compensatory). The direction of the responses (mitigating or intensifying) was identified for the different response variables considered in the studies. We also considered neutral interactions, when no change in the overall response effects when incorporating CC was detected, and mixed effects, when intensifying, mitigating, or neutral effects were found for the same response variable under different contexts. We classified as "not reported/tested" the studies that did not report or test any interaction of CC and LS to tease apart their relative effects, but mentioned the overall effect.

Finally, we explored emergent patterns of cause-effect relationships for different ecological assessment endpoints (research question 2.3 in Table 1). We performed a hierarchical cluster analysis (Ward's method) (Ward, 1963) in SPSS (version 13) to depict distinct combinations of CC effects and LS studied in the literature, and to consider the related effects represented through a Sankey diagram (Menegon et al., 2018).

3. Analyzing combined effects of climate change and human stressors

3.1. Patterns across levels of biological organization and marine provinces

Since 2008 an increasing number of publications dealing with combined multiple effects of CC and LS has been observed (Fig. A.1). We found that 25.2% of the studies analyzed ecological response to the combined effects of CC and LS at the species level, while 25.2% addressed those at the level of the trophic groups level, 22.4% at the habitat level,

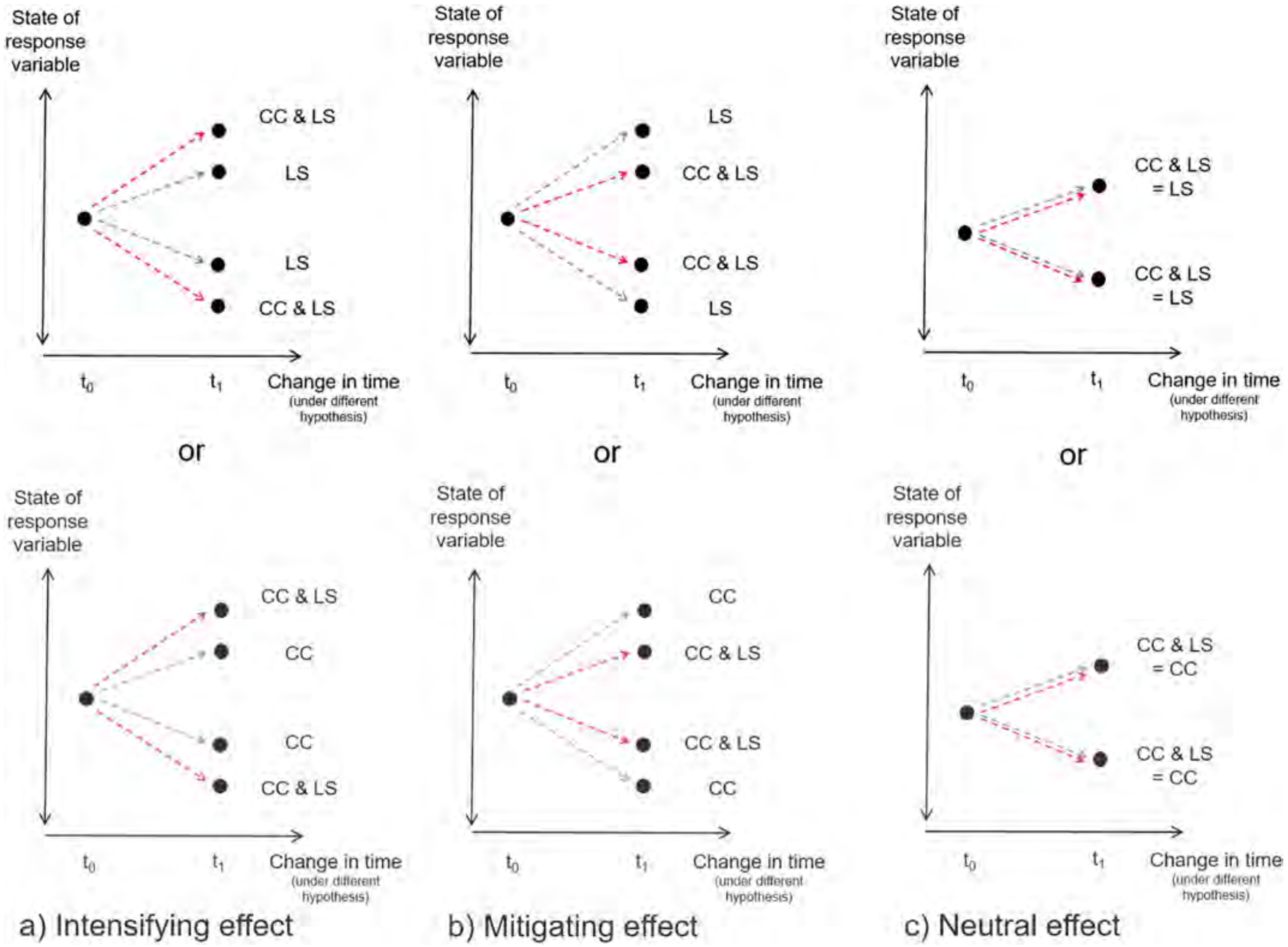


Fig. 1. Potential combined effects of climate change (CC) and human stressors (LS) on the response variable (represented by a black dot). The grey arrows represent the potential change in the state of the response variable under the effect of LS or CC only; the red arrows represent the potential change in the state of the response variable under the combined effect of CC and LS. Dashed lines indicate the passage of the response variables from an initial state to a final state in time, but not the pathway, which can be linear or non-linear. The combination effects between CC and LS are classified into three types: a) intensifying (i.e., amplification/exacerbation of the sole effect of LS or CC), b) mitigating (i.e., mitigation/dampening of the sole effect of LS or CC), or c) neutral (i.e., no significant difference is detected on the response variable between the sole effect of LS or CC, or under the combined effect of CC and LS). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and finally 27.1% at the ecosystem level (Table A.2). Interestingly, more than half of the studies at species level (59.3%) were only concerned with birds (22.2%) and fish (37.0%). At the habitat level, 25.0% of the studies focused on coral reefs. At the ecosystem level, 24.1% of the studies focused on coral reef ecosystems, and 17.2% focused on the role of microorganisms and primary production.

Among the 12 marine biogeographic realms (sensu Spalding et al., 2007), the Tropical Eastern Pacific was not covered by any regional study, but only by the seven studies addressing the combined effects of LS and CC on the entire world ocean at global scale (Fig. 2). The vast majority of the studies were located in the Northern Hemisphere (67.6%), specifically in the Temperate Northern Atlantic (46.1%), the Temperate Northern Pacific (14.7%), and the Artic (6.9%) realms (Fig. A.2). The Northern European Seas, the Mediterranean Sea, and the Cold Temperate Northeast Pacific were the most studied provinces (Figs. 2, A.2).

3.2. Methods applied in eligible studies

The analyses of the combined effects of CC and LS were conducted following different methodological approaches (Figs. 3a, A.3). Integrative assessments were applied in 25.2% of the studies, while statistical modelling – linear and non-linear – were adopted in 24.3% of studies. The remaining number of studies applied methods that span from quantitative food-web modelling to species distribution models (Fuller et al., 2015; Sarà et al., 2018), Bayesian population viability analysis (Lunn et al., 2016), individual-based models (Munroe et al., 2016), size structure matrix models (Linares and Doak, 2010), and network analyses combined with a biophysical model to measure potential functional connectivity (Grech et al., 2018). Six studies were based on expert judgment (i.e., Armstrong et al., 2019; Cook et al., 2014; Giakoumi et al., 2015; Murray et al., 2016; Singh et al., 2017; Teck et al., 2010).

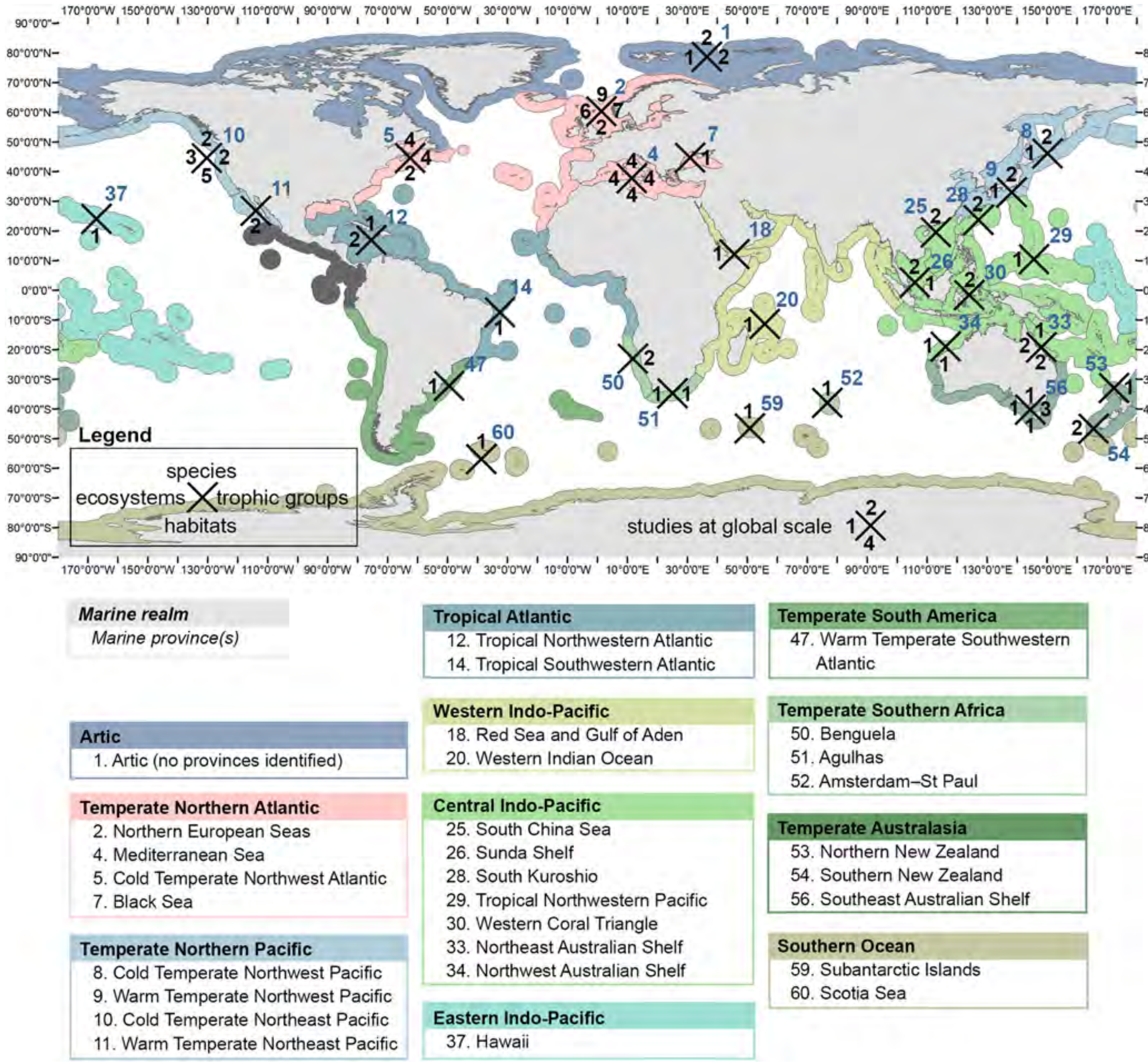


Fig. 2. Distribution among marine realms and provinces (sensu Spalding et al., 2007) of the studies for the combined effects of climate change and human stressors at different levels of biological organization, i.e., species, trophic groups, habitats, and ecosystems. The marine realms are represented with areas in different colours, and the provinces addressed by the studies are indicated with blue numbers in the figure. The Tropical Easter Pacific realm is in dark grey since there are no studies addressing the combined effects of CC and LS in this realm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

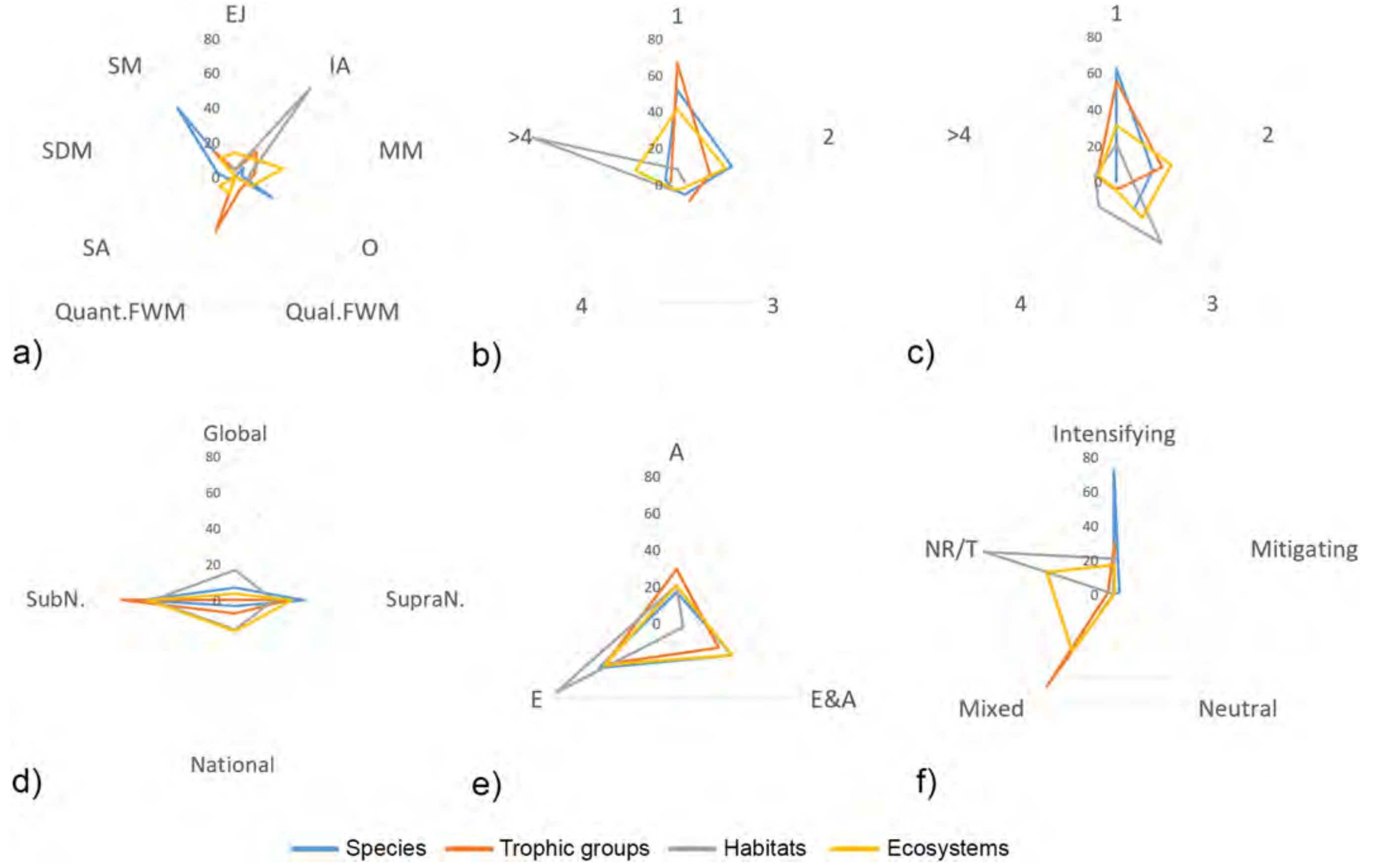


Fig. 3. Studies classification according to the level of biological organization targeted (i.e. species, trophic groups, habitat, and ecosystem levels). For each level, we reported the percentage of studies with respect to a) methods applied in the analysis of combined effects of climate change (CC) and human stressors (LS); b) number of LS in combination with effects of CC per each study; c) number of CC effects studied in combination with LS; d) spatial scales, e) temporal scales, and f) type of effects (intensifying, mitigating, neutral, mixed effects) detected by the studies. All the values are expressed as percentage of the total number of studies per each level of biological organization. In panel a) EJ = Expert judgment, IA = Integrative assessments, MM = Mechanistic modelling, O=Other, Qual.FWM = Qualitative food-web modelling, Quant.FWM = Quantitative food-web modelling, SA = Spatial analysis with GIS tools, SDM = Species distribution models, SM = Statistical modelling – linear and non-linear models. In panel d), SubN=Subnational, SupraN=Supranational. In panel e) E = Explanatory, A = Anticipatory. In panel f), "NR/T" = "Not reported/tested" refers to studies mentioning effects of CC in combination with other LS but without having tested them by disaggregating the effect of CC and the effect of LS.

3.3. Combined effects of climate change and other human stressors

We found 52 LS analyzed in combination with CC (Table A.4). The effects of industrial fisheries with CC were considered by the vast majority of the studies (72.9%), followed by the effects of shipping (25.2%), organic pollutants (24.3%), ocean-based pollution (20.6%), and artisanal fisheries (19.6%). Further, 430% of studies assessed the combined effect of a single LS with CC (mostly industrial fisheries, for 27.5% of cases), 20.6% the combined effect of 2 LS with CC, whereas the remaining studies considered 3 or more stressors in combination with CC (Fig. 3b, Table A.6). The 20 least common LS (i.e., reported in less than 3 studies each) were mostly included in studies with more than 4 stressors (27.1%), at the habitat and ecosystem levels (90.9%).

In the 107 studies analyzed, the combined effect of CC and LS was assessed for 27 CC-related effects (Table A.5). The studies combined a maximum of seven effects related to CC (Fig. 3c, Table A.7). Change in temperature was the most studied one (83.2%), followed by ocean acidification (33.6%), UV radiation (18.7%), change in salinity (13.1%), sea level rise (11.2%), and altered climatic mode of variability/climate patterns (8.4%).

Regarding the grouping of different CC effects and specific categories of LS targeted by the studies (Figs. 3c, 4), we found that change in temperature was commonly addressed with the effects of industrial fisheries (Fig. 5). The effects of sea level rise were studied in combination with a variety of 22 LS from both terrestrial and marine origin, but in particular with artisanal fishery, marine litter, introduced alien species, and change in sediment load. The LS deriving from ocean-based pollution and organic pollutants were often studied in combination with the effects of UV radiation and ocean acidification. The effects of oxygen conditions and change in salinity were often investigated with eutrophication. Other atmospheric and weather effects (e.g., change in climate patterns) and CC-induced biological drivers of change (e.g., coral bleaching derived, increase in storms) were mainly studied in combination with the least studied LS, mainly LS from maritime activities (e.g., renewable energies, military areas), terrestrial-based LS (e.g., forestry, onshore mining), and other LS (e.g., human-induced change in predator density) (Fig. 4).

3.4. Spatial and temporal scales

More than half of the studies addressing multiple effects of CC and LS were conducted at subnational scale (52.3%), 29.9% at supranational scale, whereas only 11.2% at national scale (Fig. A.4). Seven studies were conducted at a global scale (6.5%). Notably, 70.4% of the studies conducted at trophic groups level and 65.5% of those conducted at ecosystem level covered a subnational scale, while 37.5% of the studies at habitat level and the 44.4% at species level were conducted at supranational and global scales (Fig. 3d).

Combined effects of CC with LS were mainly studied in the view of explaining past effects (53.3% of the studies), i.e. through an explanatory approach. Only 21.5% adopted an anticipatory approach, and 25.2% considered both an explanatory and anticipatory approach (Fig. 3e). Out of the 51 studies that used scenario analyses to project the combined effect of LS and CC (Table A.8), 36 adopted long-term projections (i.e., from 20 to 100 years, 33.6% of all studies), 11 adopted medium-term projections (i.e., 1 to 20 years, 10.3%), and four studies adopted short-term projections (i.e., seasonal effects within a year, 3.7%) (Table A.9). Interestingly, 77.8% of studies on trophic groups have included CC effects as an indirect potential driver of impacts through scenario analysis, while only four studies on habitats (16.7%) adopted a scenario analysis (e.g., Ban et al., 2014).

4. Combined effects of climate and human stressors

Almost 70% of the eligible studies aimed to tease apart the relative effect of CC and LS, while the others focused on studying their overall effects (combined effects not reported/tested, Figs. 3f, 5). Considering studies at the species level, 74.1% reported intensifying effects, while we found a predominance of mixed effects for studies focusing on trophic groups (66.7%) and ecosystems (41.4%) (Figs. 3f, 5). The predominance of studies focusing on habitats (79.2%) did not test any interaction of CC and LS to tease apart their relative effects, but only mentioned the overall effect.

4.1. Effects at the species level

Studies at species level mainly analyzed the effect of CC with fisheries (77.8%) and with one or two other LS (66.7%). Only five studies (18.5%) combined more than two LS with CC effects. The combined effects of CC and LS on species was highly context-dependent (e.g., on the species and the specific location). It also depended on the specific LS and CC effects considered by each study. For instance, Le Bris et al. (2018) found that in Southern New England, ocean warming had an intensifying effect on American lobster (*Homarus americanus*) stocks in combination with the effects of fishery. By contrast, in the Gulf of Maine, the negative effect of ocean warming was reduced because of fishery management measures targeting large individuals and reproductive females, in combination with lower predation mortality (Le Bris et al., 2018). Another example is the case of the extent of invasion by the non-indigenous Lessepsian mussel (*Brachidontes pharaonis*) in the Mediterranean Sea. In this case CC had generally an intensifying effect, but it varied across the basin depending on variations in chlorophyll-a (due to nutrient inputs from urbanization), changes in salinity, and surface temperature (tropicalization) (Sarà et al., 2018). Changes in climate conditions in combination with other LS can have either intensifying or mitigating effects on seabird species depending on their life history (Pardo et al., 2017; Rolland et al., 2008), behavior (Burthe et al., 2014), their distribution range and latitude (Burthe et al., 2014; Rivalan et al., 2010), and seasonality of their populations (Burthe et al., 2014; Rolland et al., 2008). Across the Belize Mesoamerican Barrier Reef System, over the past century, the skeletal extension rates decline was higher for nearshore colonies of two abundant and widespread Caribbean corals (*Siderastrea siderea, Pseudodiploria strigosa*) than for the off-shore colonies, driven primarily by the combined effects of long-term ocean warming and increasing exposure to higher levels of land-based anthropogenic stressors (Baumann et al., 2019).

The effect of CC on top of other LS on species and populations was often found to be intensifying, i.e., CC amplified the effects of LS. For instance, climatic anomalies exacerbate the effects from the mechanical disturbance caused by diving frequency on populations of the sea fan *Paramuricea clavata* (Linares and Doak, 2010). Industrial fisheries that eroded the age structure of fish and thus made the population more recruitment-dependent, also made the population more sensitive to ocean warming, as in the case of Baltic herring (*Clupea harengus*) (Bartolino et al., 2014) and European hake (*Merluccius merluccius*) (Hidalgo et al., 2011). In only one case, CC and LS were found to have a mitigating effect, i.e., reducing LS-induced decline of species stock: warmer temperatures lead to faster growth/earlier maturation, allowing the population of Atlantic cod (*Gadus morhua*) to sustain higher fishing rates (Wang et al., 2014). On the other hand, when accounting for combined effects of change in both temperature and acidification with the current fishing effort, the risk of stock collapse for the Atlantic cod stock of the Western Baltic significantly increased, neutralizing the potential positive effects of only warming (Voss et al., 2019).

4.2. Effects at the trophic groups level

Fishing effort (or hunting pressure) was the most recurrent stressor studied in combination with CC at the trophic groups level (e.g., Hoover et al., 2013a, 2013b; Reum et al., 2020). Specific case studies included other emerging LS, such as turbine energy generation (Busch et al., 2013), eutrophication (Ehrnsten et al., 2019; Niiranen et al., 2013; Salihoglu and Sevinc, 2013), induced effects from coastal development (Chew and Chong, 2016).

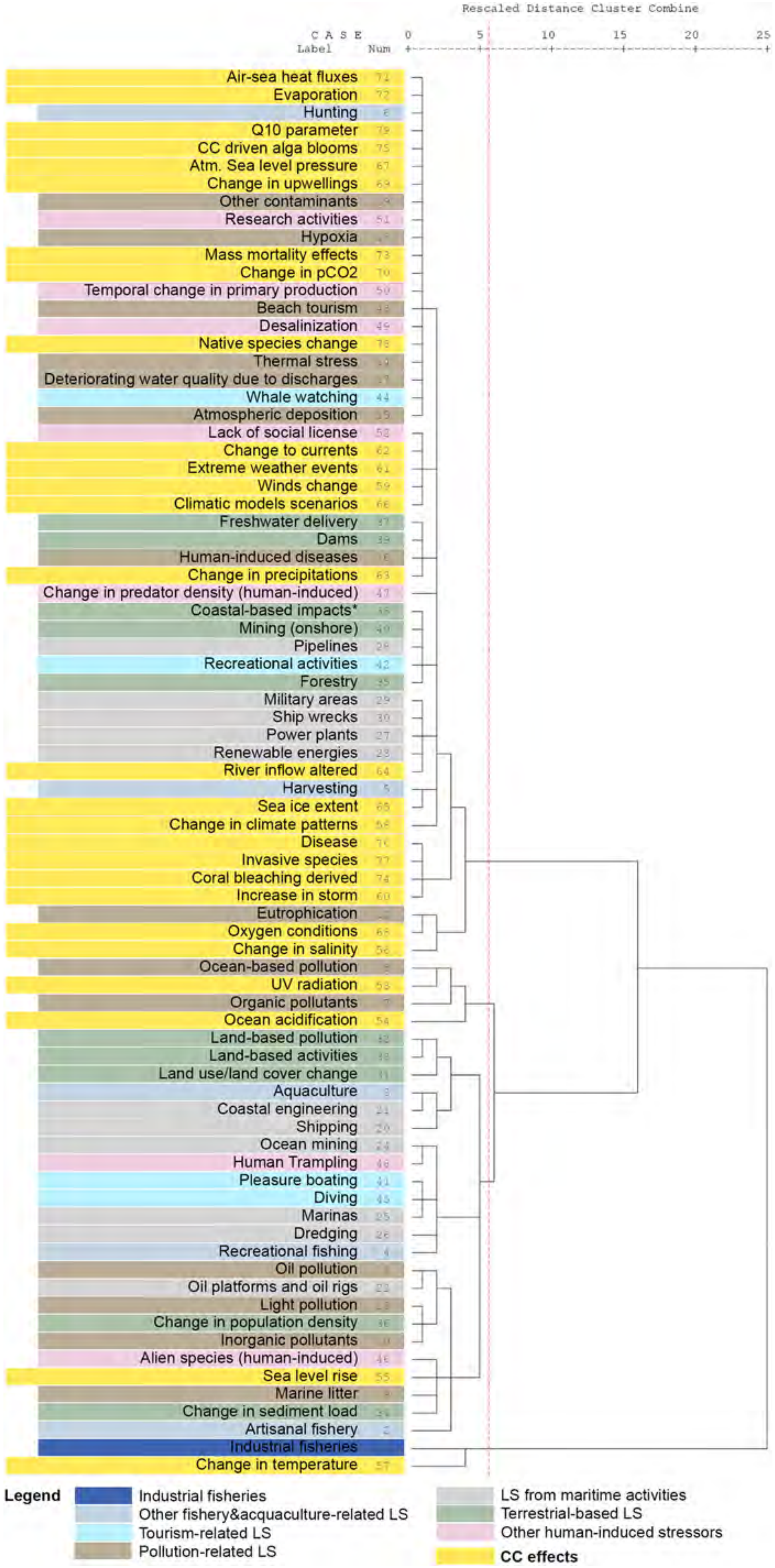
The effects of CC on top of LS varied among trophic groups at different trophic levels. In some studies, the combination of CC with other stressors did not have an additional intensifying impact on primary producers, benthic and zooplankton groups (lower trophic groups); whereas, in other studies the effects of CC on top of LS were noticeable at lower trophic levels (Kotta et al., 2009). However, as we move up the food chain, the incorporation of other effects gained importance. In general, higher trophic levels were more responsive to hunting and fishing pressures (LS), while organisms at lower trophic levels were more affected by immediate climate variations (Kotta et al., 2009). Large fish and other predators (including marine mammals, such as seals) were more intensively affected by the interaction of CC with other LS (Ortega-Cisneros et al., 2018; Serpetti et al., 2017), whereas mesopelagic fish often benefited from increasing nutrient load (often considered a stressor, coupled with fishing activity) and increased temperature, due to mitigating effects on plankton (Corrales et al., 2017; Ortega-Cisneros et al., 2018).

Also, exploited species become more sensitive to CC effects when overexploitation was occurring (Quetglas et al., 2013). Some studies showed that the cause-effect relationship clearly differs among the different pressures considered. While CC was described as a bottom-up control for communities (for instance, driving benthic species mortality), fishing was referred to as top-down control mostly responsible for changes in predatory fish biomass (Travers-Trolet et al., 2014).

The complex and specific trophodynamics of food webs made the combination of these impacts to vary between groups (Busch et al., 2013; Kotta et al., 2009; Shears and Ross, 2010). For instance, temperature dependencies on individual-level processes can impact species- and community- level variables in complex ways and are difficult to anticipate. In fact, the indirect effects of temperature that propagate through the food web may amplify or oppose direct temperature effects depending on the species (Reum et al., 2020). In most cases, the combined effects were idiosyncratic, depending on the species studied, their trophic position, and their interactions with prey and predators (Hoover et al., 2013b; Kaplan et al., 2010).

4.3. Effects at the habitat level

At the habitat level, we found that 18 out of 24 studies (75.0%) adopted the method initially proposed by Halpern et al. (2008) to quantify the combined effects of CC and LS. Cumulative impacts scores were calculated on a spatial cell grid over vast areas, for instance at national (e.g., Andersen et al., 2020; Ban et al., 2014; Teck et al., 2010), regional (e.g., Micheli et al., 2013; Rodríguez-Rodríguez et al., 2015), and global scale (Halpern et al., 2008, 2015, 2019). In all these cases, there was no actual experimental testing or modelling of the combined effect of CC and LS, but it was a priori assumed that the effects were “additive”,


Rescaled Distance Cluster Combine
C A S E
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0
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Air-sea heat fluxes
Evaporation
Hunting
Q10 parameter
CC driven alga blooms
Atm. Sea level pressure
Change in upwellings
Other contaminants
Research activities
Hypoxia
Mass mortality effects
Change in pCO2
Temporal change in primary production
Beach tourism
Desalinization
Native species change
Thermal stress
Deteriorating water quality due to discharges
Whale watching
Atmospheric deposition
Lack of social license
Change to currents
Extreme weather events
Winds change
Climatic models scenarios
Freshwater delivery
Dams
Human-induced diseases
Change in precipitations
Change in predator density (human-induced)
Coastal-based impacts*
Mining (onshore)
Pipelines
Recreational activities
Forestry
Military areas
Ship wrecks
Power plants
Renewable energies
River inflow altered
Harvesting
Sea ice extent
Change in climate patterns
Disease
Invasive species
Coral bleaching derived
Increase in storm
Eutrophication
Oxygen conditions
Change in salinity
Ocean-based pollution
UV radiation
Organic pollutants
Ocean acidification
Land-based pollution
Land-based activities
Land use/land cover change
Aquaculture
Coastal engineering
Shipping
Ocean mining
Human Trampling
Pleasure boating
Diving
Marinas
Dredging
Recreational fishing
Oil pollution
Oil platforms and oil rigs
Light pollution
Change in population density
Inorganic pollutants
Alien species (human-induced)
Sea level rise
Marine litter
Change in sediment load
Artisanal fishery
Industrial fisheries
Change in temperature
Legend
Industrial fisheries
Other fishery&acquaculture-related LS
Tourism-related LS
Pollution-related LS
LS from maritime activities
Terrestrial-based LS
Other human-induced stressors
CC effects

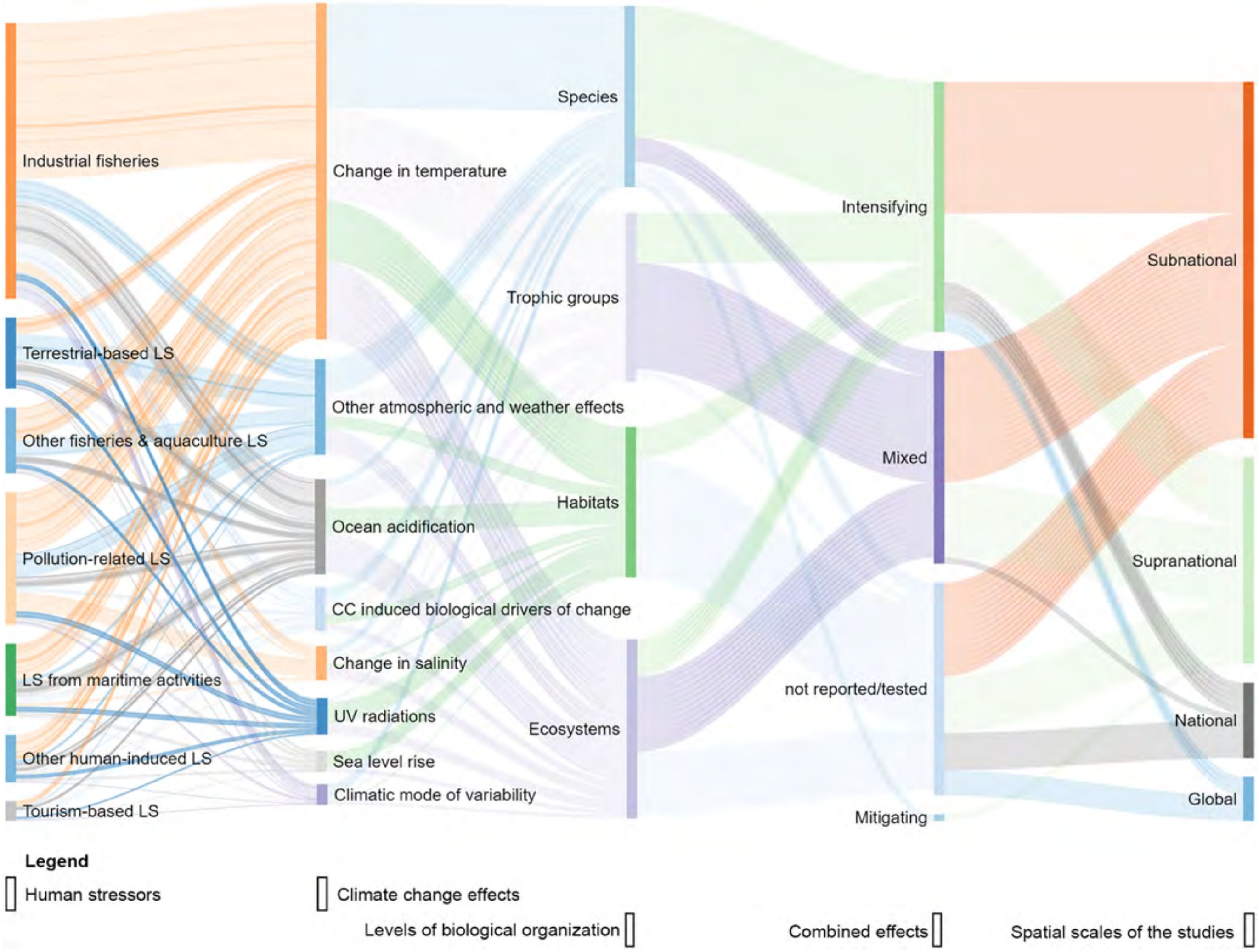

Fig. 5. Sankey diagram representing the frequency in the combination of: i) human stressors (LS) and ii) climate change (CC) effects included in the studies, iii) the different level of biological organization at which they were analyzed, iv) the resulted combined effect, i.e. intensifying, mitigating, neutral, mix, not reported/tested, and v) the geographical/spatial scale at which the studies were performed (subnational, national, supranational, global). The width of the back nodes and colored lines is proportionally to the flow quantity (produced with SankeyMATIC Visualization platform, available at http://sankeymatic.com/, accessed at 16/07/2020).

i.e. there was an intensifying (following our terminology) interaction, leading to a possible conflation of the results.

In these studies, CC effects (e.g., increase in sea surface temperature, ocean acidification, etc.) received the greatest impact scores and accounted for the majority of the cumulative impact scores. This mainly reflected the large footprint but also the widespread distribution of CC effects (Halpern et al., 2009; Magris et al., 2018; Micheli et al., 2013). For example, considering that often only a limited number of cells exhibited low levels of exposure to climatic stress, CC contributed significantly to the cumulative impact scores of the entire region under study. As a result, the impact of LS (e.g., bottom fishing) (Selkoe et al., 2009) were often masked by the spatial dominance of CC effects. Such patterns obviously had practical implications. For instance, CEAs focusing on habitats within marine protected areas suggested that CC-related stressors had the most intense impacts, supporting that mitigation actions at the MPA scale should be a high priority, at least for shallow habitats, no matter how challenging it is (Mach et al., 2017; Rodríguez-Rodríguez et al., 2015).

4.4. Effects at the ecosystem level

The response of ecosystems to the combined effects of CC and LS was complex to assess, and only 58.6% of studies at ecosystem level teased apart the effect of CC and LS. Most studies reached conclusions by looking at the most representative or abundant species of the ecosystem, e.g., looking at yellow clams as main species for sandy and beach ecosystems (Lercari et al., 2018), or at sea urchins as representative of rocky shores (Munroe et al., 2016).

The response to the combined effects of CC and LS varied significantly between and within ecosystems. For instance, in the Baltic Sea, the combined effects of eutrophication and CC on phytoplankton concentration was highly non-linear, leading to a mix of effects (Ehrnsten et al., 2019; Meier et al., 2011). The outcome may have varied both spatially and temporally and was highly dependent on the specificities of the nutrient loading and CC scenarios. Studying net primary production in the Gulf of Mexico and the East China Sea, Cai et al. (2011) found enhanced ocean acidification by the combined effect of CO_2 increase in the

Fig. 4. Hierarchical cluster analysis (Ward's method) on the combination between climate change (CC) effects and human stressors (LS) considered in the 107 studies. The red hashed line represents the clustering level at which the groups of LS clustered with at least one CC effect. CC effect clustered together with an LS effect means they are often studied in combination. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

atmosphere and increased nutrient loading. In the Northeast Atlantic, Wakelin et al. (2015) reported that direct anthropogenic forcing mitigated/amplified the effects of CC. Increasing river nitrogen had the potential to amplify the effects of CC at the coast by increasing net primary production (Wakelin et al., 2015). In the case of coral reefs, simulation tests in the Tropical Western Pacific of the effects of each of three drivers separately (i.e., CC, fishing, land based source of pollution) suggested that, by mid-century, CC will have the largest overall effect on six ecosystem metrics – i.e., i) ratio of calcifying to non-calcifying benthic groups, ii) trophic level of the community, iii) biomass of apex predators, iv) biomass of herbivorous fishes, v) total biomass of living groups, and vi) the end-to-start ratio of exploited fish groups – due to substantial intensifying effects on coral cover (Weijerman et al., 2015). The combination of bleaching derived from climate-driven increase in temperatures and fishing pressure on coral reef ecosystems of the Western Indian Ocean produced a mix of intensifying and mitigating effects (Darling et al., 2010). The effects of tropical cyclones, crown-of-thorns starfish outbreaks, and prolonged periods of high temperatures upon coral cover varied greatly in space and time across the Australia's Great Barrier Reef (Mellin et al., 2019). Coral reefs resilience was strongly and negatively related to the frequency of river plume-like conditions – as nutrient enhancement from terrestrial runoff can increase coral susceptibility to disease and temperature-induced bleaching (Thurber et al., 2014) – and, to a lesser extent, to reef accessibility, a measure of reefs remoteness (Maire et al., 2016). In general, the impacts of organic and inorganic pollution on coral reefs are expected to be intensified by climate-driven increase in temperatures, as predicted by a 'multisubstance-Potentially Affected Fraction' modelling approach (Negri et al., 2020).

5. Discussion

This study provides the first comprehensive review of the combined effects of CC and other LS on different levels of biological organizations in the context of cumulative effect assessments in the marine realm. At large, we found that the current knowledge is still very patchy and incomplete, despite the recognition that research on multiple stressors combining CC is critical for marine conservation (Ban et al., 2014; Rilov et al., 2020). This is of particular concern especially considering that worldwide, more than 40% of coastal countries are developing marine spatial planning (MSP) in their exclusive economic zones (Frazão Santos et al., 2019). We found that studies on the contribution of CC on top of LS are limited in geographical coverage, unbalanced among biogeographic realms and with some provinces completely lacking information (Lusitanian, and the Warm Temperate Northwest Atlantic Provinces). For instance, many European member states are currently undergoing MSP processes, defining areas for economic development and of conservation priority in absence of this information (Rilov et al., 2020). Therefore, there might be a risk of not achieving the objective of sustainable development, as only scattered knowledge on the potential effects of CC and LS is available in these areas.

We also found that global warming is generally studied in combination with the effects of different sectors of fishery (industrial and artisanal capture fishery, aquaculture) with idiosyncratic effects across the different levels of biological organization. Considering the economic interest of the consequences of overfishing and CC, these studies should be recognized as a priority for both research and policy makers to set the political agenda at the global scale (Mazaris and Germond, 2018). Ecosystem-based management can locally act on the negative effects of LS related to the fishery sector, and specifically where they can be potentially exacerbated by CC effects, as CC will be unavoidable at least in the short term (Frazão Santos et al., 2016). Moreover, as fishing-related activities are dominant LS within marine protected areas (Mazaris et al., 2019), the need to account for their combined effects with CC is even more urgent. Within such a framework, the identification and protection of climatic refugia (i.e., areas that are or will be less affected by CC due to the spatio-temporal heterogeneity of environmental factors) could be a promising approach for effective conservation planning (Frazão Santos et al., 2020; Keppel et al., 2015; Rilov et al., 2020) while supporting fish stocks (Ainsworth et al., 2019; Pinsky and Mantua, 2014).

Consolidated spatial management approaches, such as ecosystem-based management, aim to manage LS in relation to a set of planning objectives taking into account both space and time (Manea et al., 2019). However, we found that most studies covered a subnational scale and few studies focused on medium-term projections (i.e., 1 to 20 years), limiting our potential to set urgent management priorities for future changes at a global or regional scale. The effects of CC can be tempered in the future through distribution shifts, phenotypic plasticity, local adaptation, and contemporary evolution (Rilov et al., 2019). However, none of the reviewed studies attempted to include eco-evolutionary processes in predicting the combined effects of LS and CC; hence, our comprehension of the complex interactions between ecosystems and the changing local environment remains limited (Kelly, 2019; Urban et al., 2016).

Despite these limitations, our review provides several valuable insights, as we identified different patterns across levels of biological organization. The effects of CC on other LS at the species level were mainly intensifying ones, meaning that CC often amplifies the local detrimental effects of LS. By contrast, at the trophic groups and ecosystem levels, both intensifying and mitigating effects were observed for different functional groups in the food web context. This result suggests that further knowledge on species role and biotic interactions in response to the combination of CC and LS and in the propagation of CC effects at different trophic levels is critical deserving research priorities (Lotze et al., 2019; Voss et al., 2019; Zarnetske et al., 2012). The response in intensifying or mitigating effects depends also on the specific levels combination of LS and CC considered at each study (Reum et al., 2020; Voss et al., 2019). Therefore, determining their interaction mechanisms is essential to tailor CC mitigation by managing LS.

Adopting a combination of different approaches (e.g., correlative and manipulative studies, modelling efforts) can allow for better inference predictions of the combined effects of CC and LS. In the laboratory, stressor effects can be carefully isolated (Crain et al., 2008), but given the complexity of natural ecosystems and food webs, there is a challenge of scaling-up and transfer the observed species responses to the "real world" (for a discussion on challenges and opportunities of scale in enclosed experimental ecosystems research see Petersen et al., 2009, Petersen and Kemp, 2019). Still poorly employed in ocean change research (Riebesell et al., 2013), infield mesocosm systems, such as the mobile sea-going Kiel Off-Shore Mesocosms for Future Ocean Simulations (Riebesell et al., 2013), aim to improve conditions of the experimental setups (Petersen and Kemp, 2019, Riebesell et al., 2013), which could offer a valuable piece of information for scaling-up processes. In addition, the assessment of an increased number of combinations of CC and LS is needed to document their individual and interactive effects (Boyd et al., 2018). When exploring in the field complex direct and indirect effects of CC and LS on ecosystems, experimental manipulation can be impractical (Kirby et al., 2009), with considerable expense and logistical difficulties (Boyd et al., 2018), and could even be considered unethical at the scale of an ecosystem (Kirby et al., 2009). Large-scale collaborative studies should be adopted to fill these gaps in combination with modelling studies, especially serving management and planning. Furthermore, well managed MPAs, where local stressors are partly controlled, can serve as natural laboratories to separate the impact of CC from local stressors such as fishing and pollution (Rilov et al., 2020).

In many studies of cumulative effects on habitats, the data used as indicators of CC do not often accurately reflect or predict the actual impacts upon biotic components (Halpern et al., 2009). Under this context, the fact that CC contributed significantly to the overall cumulative impacts scores – as for instance, in Halpern et al. (2008) – might reflect a theoretical concern rather than the actual impact upon marine habitats (Kappel et al., 2012). The fact that CC stressors are often treated as ubiquitous (Jones et al., 2018) could also hinder an additional source of bias due to a key assumption that they act mainly synergistically – i.e., amplifying – with other stressors. CC effects can be different even at different parts of the distributional range of a species, stressing the need to consider ocean weather (variability) in our studies (Bates et al., 2018). Indeed, Darling et al. (2010), studying the role of thermal-stress (leading to prolonged coral bleaching, and often mass mortality) and fishing on Kenyan coral reefs, demonstrated that the interaction could be 'weakly additive' (i.e., intensifying), even 'antagonistic' (i.e., mitigating). Examining the relative importance of thermal stress and of suspended sediment pressure pathways driven by dredging in predicting coral mortality in Barrow Island (Western Australia), Fisher et al. (2019) found that "low to moderate reductions in available light associated with dredging may lead to 'weak antagonistic' (i.e., mitigating) cumulative effects" (p.1). However, when sediment loads were high, severe low light periods and high levels of sediment deposition produced synergistic (i.e, intensifying) effects on coral mortality (Fisher et al., 2019). Similar results were found when investigating the effect of fishing and changes in primary productivity on fish communities using a multi-modelling approach (Fu et al., 2018). Thus, understanding the mechanisms and effects of single stressors is key to predict the nature of their interactions, and the hypotheses on such interacting mechanisms require validation through continued empirical tests (Crain et al., 2008) and multi-modelling exercises (e.g., Reum et al., 2020).

The ability of reporting the combined effects of CC on top of LS is highly dependent on the study design and related methods applied in the different studies. Since CC effects are subjected to a significant range of variability according to the various IPCC scenarios (IPCC, 2019), we would have expected that the majority of studies would have applied a scenario analysis, but it was applied only in 48.1% of the studies. When addressing the combined effects of CC and LS, forecasting forward under multiple scenarios is essential, since different levels of LS and CC can result in different combined effects, as we found in our analysis. For instance, Voss et al. (2019) found that the risk of stock collapse of western Baltic cod changed according to different (and combined) levels of ocean warming, acidification, and fishery under multiple scenarios. In the case of the Eastern Bering Sea food web, for some species, mixed effects were observed depending on the combination of climatic scenarios and fisheries management scenarios (Reum et al., 2020). In the Central Baltic sea food web, scenarios combining intensive cod fishing and high nutrient loads projected a strongly eutrophicated and sprat-dominated ecosystem, whereas low cod fishing in combination with low nutrient loads resulted in a cod-dominated ecosystem with eutrophication levels close to present (Niiranen et al., 2013). Multi-factorial CC research that combines CC projections and management scenarios is essential to provide the "best available, most realistic, and precautionary advice" (Voss et al., 2019) for ecosystem-based management (Bartolino et al., 2014; Gissi et al., 2019; Voss et al., 2019). Much more attention should be devoted to integrate scenario analysis, reflecting on the sources of uncertainties entailed in the scenarios (Gissi et al., 2019; Stelzenmüller et al., 2013) and transparently communicating uncertainty for robust decision making (Gissi et al., 2017; Stelzenmüller et al., 2020).

Future research should be able to differentiate the responses to the stressors that we can manage to reverse, from the ones to which we have to adapt at local scales (Ramírez et al., 2018). The temporal and spatial scales at which the methods are meaningfully applied are also essential in order to explore the combined response of CC effects and LS. Long-term monitoring and related datasets and systems are needed in order to study changes in structure and functionality at different levels of biological diversity over future CC scenarios. Anticipatory studies can capitalize on explanatory studies of future CC effects. Our results indicate that the studies on multiple effects between CC and LS mainly focused on long-term environmental dynamics. Only few studies focus on rapid shifts (extreme events) or responses due to, for instance, cyclones and heat waves (e.g., Grech et al., 2018; Shears and Ross, 2010). Especially for events such as heat waves, long-term data and monitoring at the right temporal and spatial scale are needed. Different kinds of temporal data are needed to depict long-term responses as well as short-term abrupt shifts, such as historical, real time and continuous data and adaptive monitoring (Rilov et al., 2020). In this regard, state-of-the-art models seem to fail to capture such short-term environmental dynamics to date (Schewe et al., 2019), thus modelling tools and data availability are also challenged to properly capture such events.

Finally, the simplified classification proposed in this study (recently introduced by Montero-Serra et al., 2019) was appropriate to understand the outcomes of the combined effect of LS and CC with respect to the different response variables considered by the studies. The knowledge on the direction of the expected responses (i.e., intensifying or mitigating effects) is essential to differentiate management interventions accordingly (Côté et al., 2016). Though the definitions of interactions have been revised over time (e.g., Côté et al., 2016; Crain et al., 2008; Folt et al., 1999; Piggott et al., 2015), a transparent and consistent use of the terminology among studies addressing the response to multiple stressors would be beneficial to understand recurrent response patterns at multiple scales and at multiple biological levels.

6. Conclusions

Beyond taking immediate responsibility at the global, national and individual levels to reduce CO_2 emissions to curb the unfolding impacts of CC (IPCC, 2019), our findings stress the need to also act fast on what we can locally manage to reduce other LS, which can be exacerbated by CC effects. Combined effects of CC and LS are context-dependent, varying between and within ecosystems. These results clearly call for specific studies to depict context-based responses in order to robustly inform management processes. Within this framework, aiming to maintain ecosystems at a "safe operating space" (sensu Rockström et al., 2009), i.e., within boundaries of ecosystem collapse because of locally human-induced drivers of change (Ramírez et al., 2018), can be a promising approach to effectively counteract CC impacts by managing local LS.

Despite the progresses on understanding the effects of CC in combination with LS, we identified a substantial gap of knowledge on LS. Beside the main focus on few large-scale LS – e.g., fishery-related LS combined with ocean warming, or pollution with ocean acidification – there are many LS whose combined effects with CC are under-studied, such as renewable energies, ocean mining, or coastal tourism. This knowledge gap will limit our potential to effectively manage the complete set of LS, considering the increasing number of human uses boosted by Blue Growth initiatives worldwide (Gissi et al., 2018; Klinger et al., 2018).

Besides the inherent uncertainties on spatial and temporal effect sizes of the combined effects of CC and LS, decisions on the regulation of LS have to be taken at rather short terms. This calls for the urgent need of CEAs to formalize such integrated assessments. CEAs should form a key part in ecosystem-based management and planning processes, which regulate the spatial and temporal distribution of human activities, to enable a better consideration of the combined effects of LS and CC effects.

CRediT authorship contribution statement

Elena Gissi: Conceptualization, Methodology, Data curation, Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **Elisabetta Manea:** Data curation, Investigation, Writing - review & editing. **Antonios D. Mazaris:** Methodology, Investigation, Writing - review & editing. **Simonetta Fraschetti:** Methodology,

Investigation, Writing - review & editing. **Vasiliki Almpanidou:** Investigation, Writing - review & editing. **Stanislao Bevilacqua:** Investigation, Writing - review & editing. **Marta Coll:** Investigation, Writing - review & editing. **Giuseppe Guarnieri:** Investigation, Writing - review & editing. **Elena Lloret-Lloret:** Investigation, Writing - review & editing. **Marta Pascual:** Investigation, Writing - review & editing. **Dimitra Petza:** Investigation, Writing - review & editing. **Gil Rilov:** Investigation, Writing - review & editing. **Maura Schonwald:** Investigation, Writing - review & editing. **Vanessa Stelzenmüller:** Investigation, Writing - review & editing. **Stelios Katsanevakis:** Investigation, Writing - review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary information

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