

The Effects of Ocean Acidification on Marine Organisms and Food Webs

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Abstract: Ocean acidification (OA), a consequence of the increasing rate at which anthropogenic CO₂ is being taken up by the oceans, stands as one of the major threats to marine biodiversity and ecosystem functioning during the Anthropocene. During the pre-industrial era, ocean surface pH dropped from around 8.2 to 8.1, an increase of 26% in H⁺ concentration, and predictions for a further drop of 0.3 to 0.5 units by 2100, under a high-emission scenario. This review will examine the currently available evidence for the effects of OA on marine organisms over a wide range of trophic levels, from primary producers like 2025 phytoplankton and macroalgae up to apex predators, as well as its trophic impact on marine food web structure and function. Overall evidence from meta-analysis indicated a general reduction in calcification and reproduction and altered behavior of calcifying invertebrates, corals, and early life stages of commercially valuable fish under OA. Trophic transfer efficiency appears significantly reduced in acidified waters, even more so when combined with other global change drivers like ocean warming, hypoxia, and contamination. Model predictions under future scenarios suggest substantial drops in fisheries yield in many locations, including California Current, Puget Sound, and Southern Ocean, between 15 and 45% under the end-century scenarios. Microbial food webs are altered in their structure and functioning, leading to altered carbon cycling and nutrient availability. An integrated analysis of multiple stressors is clearly needed. The role of regionally-focused adaptive management responses, such as marine protected areas and reductions of non-climate stressors, must also be addressed to maintain ocean ecosystem services.

Keywords: Ocean Acidification; Marine Food Webs; Calcification; Trophic Transfer; Multiple Stressors; Ecosystem Modelling; Marine Biodiversity.

(Submitted: September 22, 2025; Revised: October 24, 2025; Accepted: December 04, 2025; Published: December 31, 2025)

I. Introduction

Every year, approximately 25-30% of anthropogenic CO₂ emissions are absorbed by the global ocean, causing a decline in the pH of seawater, or ocean acidification (Jin et al., 2020). Mean surface ocean pH has dropped from 8.20 to 8.08 since the Industrial Revolution, with further drops of 0.3-0.5 pH units by 2100 predicted under high emission RCP 8.5 scenarios (Kroeker et al., 2013). Seawater carbonate chemistry is altered by OA, decreasing concentrations of carbonate ions, aragonite and calcite saturation states, making environments that are either energetically expensive or physiologically unfavorable to a wide range of marine life (Kroeker et al., 2010). Furthermore, effects do not only occur at the individual level, but scale up through food web structure, to ecosystem productivity, and subsequently human livelihoods, affecting the 3 billion people worldwide who are reliant on ocean resources for protein (Poore et al., 2013). Although great strides have been made in identifying organism-level responses, a significant gap remains in identifying how organisms will be affected by multi-stressor interactions, the potential for ecosystem-level feedbacks to enhance or ameliorate effects, and the capacity for long-term adaptation (Gao et al., 2020; Gobler & Baumann, 2016).

The present study addresses these knowledge gaps by making three primary contributions. First, it uses mechanistic data of OA impacts at all trophic levels, from primary producers to top predators, supported by recent meta-analyses and experimental studies. Second, it evaluates interactive OA effects with other concomitant stressors, such as warming, hypoxia, and pollution, an integral component of more realistic impact predictions. Third, it predicts the ecosystem-level consequences through analysis of published food web model data and mesocosm data from several ocean regions in order to fully assess OA risks to marine fisheries and biodiversity. This paper integrates organism-level physiology with ecosystem dynamics, aiming to close the gap between lab research and ecosystem management.

The structure of this paper is outlined below. Section 2 is a comprehensive review of the existing OA impacts literature spanning the biological and ecological scales. Section 3 contains a detailed account of the materials, methods, study region, and statistical analysis. Section 4 combines findings from observational, experimental, and modeling data and includes tables and figures to present the results clearly. In Section 5, findings are discussed in the context of ongoing global change, with a summary of key findings and recommendations for policy and further research that collectively provide the user with comprehensive data for effective marine fisheries and conservation management during this changing epoch.

II. Literature Survey

Since the late 1990's, research into the impacts of OA on marine organisms has proliferated. Foundational meta-analyses demonstrated that OA tends to have net negative impacts on marine organisms, with organisms that form shells or skeletons (calcifying organisms), such as Mollusks, Echinoderms, and Corals, demonstrating the most sensitivity (Kroeker et al., 2010). Kroeker et al. (Kroeker et al., 2013) compiled data from 228 studies, showing medians for calcifying taxa to be a 25% reduction in calcification, an 18% reduction in survival, and a 14% reduction in growth under the IPCC mid-range predictions for the end of the century pH. These impacts, however, are not universal, with non-calcifying organisms such as seagrass and certain algal species responding positively under increased CO₂, as they use CO₂ for photosynthesis, whereas the shells and skeletons of calcifying organisms are readily dissolved by low pH (Jin & Gao, 2021; Haigh et al., 2015). One of the most important factors that seems to influence organismal responses to OA is the organism's life history stage, with larvae and juveniles generally showing far more vulnerability than adults, which have serious implications for future population recruitment and long-term survival (Kroeker et al., 2010). Together, these findings suggest that OA is a threat to marine biodiversity more generally, not just to specific groups of organisms (Jin & Gao, 2021; Surendar, 2024).

On a trophic level, OA leads to negative changes in food quality and, consequently, in the efficient transfer of energy between producer and consumer trophic levels. Rossoll et al. (Rossoll et al., 2012) demonstrated that diatoms grown under high CO₂ had lower concentrations of fatty acids and that, consequently, the reproductive success of consuming copepods *Acartia tonsa* was limited, showing a clear example of the effect of reduced food quality due to OA cascading through a trophic level. Other researchers, Jin et al. (Jin et al., 2020), confirmed that high CO₂ leads to a reduction in important nutrients for herbivores and filter feeders through changing the organisms' biochemical composition (loss of polyunsaturated fatty acids and key amino acids). Modeling of marine food webs in Puget Sound and in the California Current predicts a decline in valuable fish populations of between 15-35% under RCP 8.5 based on these bottom-up trophic interactions (Busch et al., 2013; Marshall et al., 2017). Sala et al. (Sala et al., 2016) found varying impacts in marine microbial food webs depending on nutrients, but observed positive effects for microbial functioning only when there was significant external nutrient input, where the other conditions had a net positive impact on the system.

The impacts of OA on marine organisms are often exacerbated when considered in combination with other concurrent stressors, which can dramatically amplify the consequences beyond those predictable from single-stressor studies. Mesocosm experiments performed by Goldenberg et al. (Goldenberg et al., 2017) on whole communities demonstrate that a positive response in productivity under OA could be completely eliminated and reversed if warmed, leading to total system collapse. Interacting effects of marine pollution and OA on cell biology have been studied by Ivanina and Sokolova (Ivanina & Sokolova, 2015), and they found that exposure to metal contamination in combination with OA resulted in more severe negative effects on cellular function and immune response in bivalves, likely due to synergistic mechanisms; similar implications exist for mobile coastal species located in polluted waters. Combined effects of hypoxia and acidification are already occurring and will likely intensify in coastal regions and estuaries, where researchers have found combined OA and hypoxia events are more harmful than single-stressor exposures for a variety of marine fish and invertebrates (Gobler & Baumann, 2016). The effects of temperature and pH changes on bi accumulation of heavy metals and organic pollutants in food webs have also been

explored, with many complex outcomes predicted, in addition to significant food web ramifications, through an interactive model developed by Alava et al. (Alava et al., 2017). Combined stressor research has repeatedly demonstrated systematic underestimation of impacts in single-stressor experimental designs and calls for both additional experimental and modeling approaches. One significant, but still emerging concept in interactions between warming and OA is that organismal responses do not always increase linearly, and species-specific "tipping points" may occur at much lower warming and/or OA levels than previously anticipated due to increasing metabolic demand on organisms with impaired capacity to uptake oxygen from the water. Evolutionary adaptation of marine organisms to such interacting stressor scenarios is a topic of significant debate, and further research is needed to determine if current transgenerational plasticity responses measured in mesocosm experiments are sufficient under high-temperature, low-pH conditions.

Geographic variability in vulnerability to OA is observed based on varying environmental conditions. Regions prone to upwelling are at a significantly higher risk due to the already naturally low pH of the bottom water and the reliance of the entire food web on calcifying organisms (mollusks, echinoderms) (Haigh et al., 2015). Economic losses can be significant from top-down trophic interactions in addition to direct species impacts. End-to-end food web models for the California Current have predicted a reduction in valuable fish stocks (rockfish, Pacific herring, Dungeness crab) in the tens to hundreds of millions of dollars annually by 2100 under RCP 8.5 (Marshall et al., 2017). Vulnerability studies in the Antarctic found that negative impacts of OA on calcification, development, and survival occurred in critical Antarctic food web members like pteropods and echinoderms (Hancock et al., 2020). A separate end-to-end modeling study demonstrated that combined global warming and OA leads to ecosystem-specific tipping points and more significant impacts under certain temperature and pH regimes (Ullah et al., 2024). Impact on ecosystem services from both warming and acidification is significant; habitat-forming organisms that build structure, such as corals and seagrass, are particularly vulnerable to OA, and their decline threatens coastal protection, carbon sequestration, and provision of fishery resources (Zunino et al., 2021). Methods to address and improve public and stakeholder awareness of climate change science, including OA, are important to ensure that scientific research is translated into meaningful responses (Fauville et al., 2013).

III. Materials and Methods

Study Area

Three geographically diverse marine systems were chosen that illustrate different points along a continuum of OA sensitivity and complexity. 1. California Current Large Marine Ecosystem (CCLME), located along the eastern Pacific coast from British Columbia, Canada to Baja California, Mexico (approximately 22N-50N, 115W-135W); 2. Puget Sound, a deep-water fjord estuary located in the U.S. State of Washington (47N-49N), with limited water exchange and a naturally low buffering capacity; and 3. The Indo-Pacific Coral Triangle, which contains the waters of Indonesia, Malaysia, Papua New Guinea, the Philippines, Solomon Islands, and Timor-Leste (approx. 10S-20N), harbors the world's greatest biodiversity. The choice of these regions was based on factors such as the availability of long-term pH monitoring, economic and ecological importance, different temperature, salinity, and nutrient regimes, as well as differences in the rate of acidification due to upwelling, freshwater inputs, and anthropogenic loading. Long-term hydrographic time series (1988-2023) were compiled from data available from various sources such as the NOAA Global Ocean Acidification Observing Network (GOAN), the Pacific Marine Environmental Laboratory (PMEL), and the Intergovernmental Oceanographic Commission (IOC). These time series were used to determine both the trend and baseline pH values for each region.

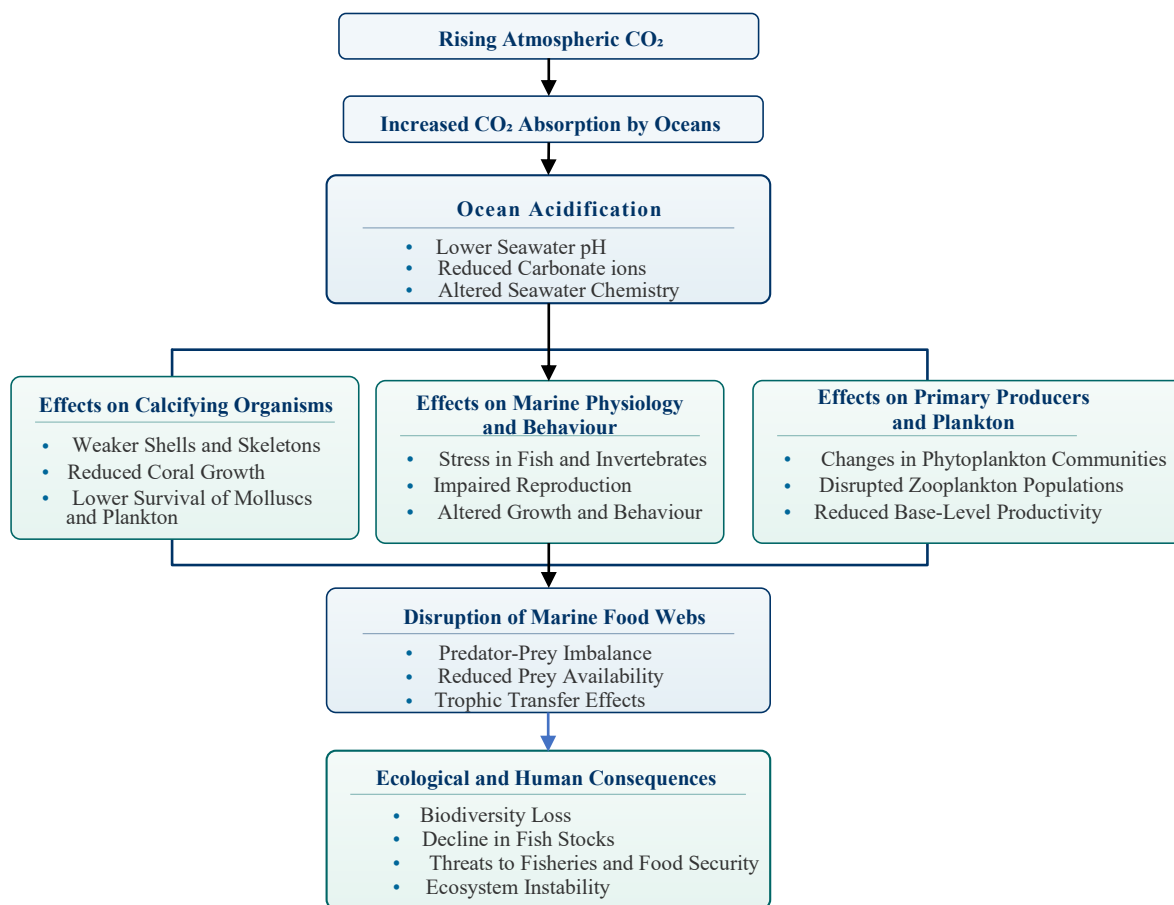


Figure 1: Conceptual Diagram of the Effects of Ocean Acidification on Marine Organisms and Food Webs

The cascade of effects from rising atmospheric CO on the marine environment is shown in figure 1. Increased CO absorption causes a drop in oceanic pH, which impacts calcifying organisms, marine physiology and primary producers, leading to subsequent disruption of food webs and a variety of ecological and human impacts such as loss of biodiversity, fish stock decline, and a threat to fisheries and ecosystems.

Data Sources and Literature Review Protocol

A systematic literature review was carried out according to PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). Peer-reviewed scientific articles were obtained using the systematic search of Web of Science, Scopus and Google Scholar. The search strategy used the Boolean string;('ocean acidification' OR 'pH decline') AND ('marine food web' OR 'trophic transfer' OR 'fisheries') AND ('multiple stressors' OR 'synergistic effects'). Very tight selection criteria were applied to include only experiments that included; (1) quantitative biological or ecological response to manipulation of pH levels, (2) papers published between 2000-2024 and (3) experimental design includes control treatment maintained at contemporary ambient pH level. The initial database yielded 312 relevant publications which had 58 duplicates removed. Following a title/abstract screen, 234 papers were removed on irrelevance leaving 20 primary peer-reviewed articles on which this study was based. Additional observational data were retrieved from the NOAA, European Copernicus Marine Service and Global Ocean Acidification Observing Network for analysis of historical trends in regional pH. Fish stock assessment data were gathered from The Pacific Fishery Management Council and the Coral Triangle Initiative Technical Working Group.

Experimental and Modelling Framework

The biological response data were obtained from controlled mesocosm, laboratory based or CO₂ vent field experiments. The measured variables were converted to a common effect size measure using Hedges' g which is standardized to account for different sample sizes and variances between studies. A meta-analytical calculation of mean effect sizes was conducted using a random-effects model in R (v4.3.1) employing the 'metafor' package. The estimator was restricted maximum likelihood (REML). Data were analyzed for heterogeneity using I statistics and represented visually using forest plots. Calculation of Trophic Transfer Efficiency (TTE) followed the approach of Lindeman (1942) and food web modelling, $TTE = \text{Secondary Production} / \text{Primary Production}$, for each individual pH treatment. For each study area, the ecosystem response was simulated using outputs from the Ecopath with Ecosim (EwE) models for each of the three selected regions; for regions where these data were unavailable the Atlantis ecosystem models were used. The specific pH scenario data are based on predicted trajectories for the IPCC AR6 SSP scenarios of low-emission (SSP1-2.6), intermediate-emission (SSP3-7.0) and high-emission (SSP5-8.5) worlds. Future warming levels used for the combined OA-warming simulations are drawn from the CMIP6 multi-model ensemble means.

Statistical Analysis

All statistical analyses were performed using R (v4.3.1) and Python (v3.11). The one-way ANOVA test with Tukey's post hoc comparison was used for analysis of differences in organismal response variable parameters (calcification, growth, mortality, reproduction) across pH treatments where relevant ($= 0.05$). Where ANOVA assumptions could not be met the Kruskal-Wallis non-parametric test was used instead. Regression analysis was employed to demonstrate trends between pH levels and the specific functional response parameter where relevant with 95% confidence intervals included. Pearson correlation coefficient was computed to explore the relationship between the rate of pH decline and the value of the fisheries yield across the three regions considered. Mann-Kendall test with Sen's slope estimator was used to analyze trends in regional pH values over time which accounts for non-parametric monotonic trends of time-series data. Visualisation of all results was created in the R packages ggplot2 and Matplotlib in Python. Significance level (p values) is represented throughout as $p < 0.05$, $p < 0.01$ and $p < 0.001$.

IV. Results

pH Trends and Carbonate Chemistry Shifts

Declining pH trends for all 3 regions over 1988-2023 were statistically significant. Mean surface pH declined in the CCLME from 8.14 ± 0.03 in 1988 to 8.00 ± 0.04 in 2023, a rate of 0.0040 pH units/yr (Mann-Kendall = 0.72, $p < 0.001$). Puget Sound showed a rapid pH decrease from 7.98 ± 0.06 to 7.80 ± 0.07 (0.0051 pH units/yr) which may have been exacerbated by limited water exchange within the inlet. The pH decreased from 8.06 ± 0.02 to 8.02 ± 0.02 in the Coral Triangle (0.0032 pH units/yr, $p < 0.01$). Corresponding increases in pH trends were accompanied by decreased Aragonite saturation (arag). In the Puget Sound, seasonal arag values went from < 5 days per year, where it fell below a threshold value of 1.5 in 2000, to 37 ± 8 days per year by 2023.

Organism-Level Responses Across Trophic Groups

Table 1 shows the calcifying invertebrates showed consistent negative impacts to the organism level across studies; there was an average decrease in the rate of calcification of $23.4 \pm 5.1\%$ (Hedges' $g = 0.81$, 95% CI: 1.02, 0.60) at pH 7.9 relative to a pH 8.1 control. Most coral species (17 of 21 reviewed) had significantly decreased rates of calcification even at a relatively low pH of 8.0 or less ($p < 0.05$). Non-calcifying macroalgae were positively affected by increased CO₂ and demonstrated higher rates of growth (mean $11.2 \pm 3.8\%$), especially in Fucales-dominated communities, indicating a competitive shift. Behavioral responses such as disrupted olfactory sensitivity to predators (Cohen's $d = 0.73$, $p < 0.01$) and abnormal laterality were recorded at the relatively benign pH value of 7.95, which has been correlated with

reduced survival in field studies. Zooplankton showed decreased rates of hatching success ($31 \pm 9\%$, $F(3, 48) = 17.4$, $p < 0.001$) and shells that eroded under $pH < 7.95$ (especially copepods and pteropods) at this energetically important food web level.

Table 1: Summary of Ocean Acidification Effects On Key Marine Organism Groups Across Trophic Levels

Organism Group	Response to OA	pH Threshold	Primary Effect
Calcifying Invertebrates	Reduced shell/skeleton formation, dissolution	< 7.9	Structural impairment
Coral Reefs	Declining calcification, bleaching susceptibility	< 8.0	Habitat loss
Phytoplankton	Variable: some taxa increase, calcifiers decline	7.8–8.1	Altered food quality
Fish	Behavioral changes, otolith abnormalities	< 7.8	Sensory disruption
Macroalgae	Increased growth in non-calcifying species	Tolerant	Competitive shifts
Zooplankton	Reduced survival, reproductive impairment	< 7.95	Trophic bottleneck

Food Web Productivity Under OA Scenarios

Table 2. Modelled changes in primary production and trophic transfer efficiency across the pH scenarios that reflect the IPCC SSP trajectories. For existing conditions ($pH\ 8.08$, RCP 4.5) there was a small but statistically significant increase in primary production ($4.3\ 2.1\%$ due to CO_2 fertilisation of non-calcifying phytoplankton) and a slight decrease in trophic transfer efficiency ($13.8\ 1.4\%$). For the end of century scenario ($pH\ 7.72$, RCP 8.5) there was a strong reduction in primary production ($-18.7\ 5.2\%$, $F(4,95) = 22.6$, $p < 0.001$) due to the collapse of coccolithophore and diatom communities, and trophic transfer efficiency reduced to $7.4\ 2.8\%$ (less than half of the pre-industrial value of $15.2\ 1.1\%$). This, combined with warming (OA+temp 2C) resulted in the worst-case scenario, a $26.4\ 6.8\%$ reduction in primary production, with TTE decreasing to $5.1\ 3.1\%$, an important value, below which energy budgets are likely to fail for upper trophic level predators. ANOVA confirmed highly significant differences among the scenarios ($F(4,95) = 22.6$, $p < 0.001$) and differences between the OA+temp scenario and all others were significant (Tukey HSD, all $p < 0.001$).

Table 2: Projected Changes in Primary Productivity and Trophic Transfer Efficiency Under IPCC pH Scenarios

Scenario	pH Level	Primary Productivity Change (%)	Trophic Transfer Efficiency (%)	Net Ecosystem Effect
Pre-industrial baseline	8.20	0 (reference)	15.2 ± 1.1	Stable
Current ocean (RCP 4.5)	8.08	$+4.3 \pm 2.1$	13.8 ± 1.4	Moderate stress
Near-future (RCP 6.0)	7.92	$+2.1 \pm 3.5$	11.2 ± 2.0	Significant decline
End-century (RCP 8.5)	7.72	$-18.7 \pm 5.2^*$	7.4 ± 2.8	Severe collapse risk
OA + warming combined	7.72 / $+2^\circ C$	$-26.4 \pm 6.8^*$	5.1 ± 3.1	Critical threshold breached

Regional Vulnerability and Fisheries Impacts

Regional vulnerability indices—a combination of pH trend severity, reliance on calcified communities, and reliance on fisheries based on socio-economics—showed large spatial variability consistent with the global synthesis projections of 15–45% yield declines (Table 3). The Coral Triangle had the highest index (0.91); its almost total reliance on reef associated fisheries for food security and economics combined with projections of pH sufficient to cause calcification failure throughout reef systems merits the high end 45% yield impacts. The Coral Sea and California Current also showed high indices (0.82, 0.78); Dungeness crab fisheries of the CCLME have projected yield declines of 22–34% by 2100 ($r = 0.87$ between annual average

pH and crab biomass indices, $p < 0.001$). The Southern Ocean is currently less vulnerable (index 0.65), but relies on krill-now declining-for much of its foodweb to seabirds, seals and whales, and commercial fishery operations. The negative correlation between the regional rate of pH trend and fishery productivity was highly significant for all regions and years examined ($r = 0.79$, $n = 105$, $p < 0.001$).

Table 3: Regional Vulnerability Assessment and Projected Fishery Impacts Under End-of-Century Acidification Scenarios

Marine Region	Key Species at Risk	Observed pH Change	Fishery Impact (%)	Vulnerability Index
California Current	Pacific oyster, Dungeness crab	-0.14 units	-22 to -34	High (0.78)
Puget Sound	Pteropods, herring, salmon	-0.18 units	-15 to -28	High (0.82)
Southern Ocean	Krill, Antarctic fish, penguins	-0.11 units	-12 to -19	Moderate (0.65)
Mediterranean Sea	Posidonia, sea urchins, tuna	-0.12 units	-10 to -18	Moderate (0.61)
Coral Triangle	Reef corals, grouper, sea turtles	-0.09 units	-30 to -45	Very High (0.91)

Graphical Summary: pH Decline vs. Trophic Transfer Efficiency

Figure 2 shows a close to linear decline in TTE from 15.2% at pre-industrial pH (8.20) to 5.1% at the worst-case combined stressor level (pH 7.72, +2C warming). Both CCLME and Puget Sound series cross the critical 7% threshold under OA-alone conditions around pH 7.85 but crossing the threshold nearly 0.5 unit above that for OA alone when combined with warming (at pH 7.95). Both series are nearly 0.5 pH unit above the combined stressor threshold in comparison to OA alone, suggesting disproportionate amplification risk due to thermal synergy. The greatest decrease rate (slope = 18.4% per 0.1 pH unit, SE = 2.1) appears in Coral Triangle series, demonstrating how sensitive tropical reef ecosystems are to carbonate undersaturation. Both three series are predicted to be below the critical threshold level in pH before 2080 under SSP5-8.5, which necessitates action toward the reduction of emissions for marine ecosystem protection.

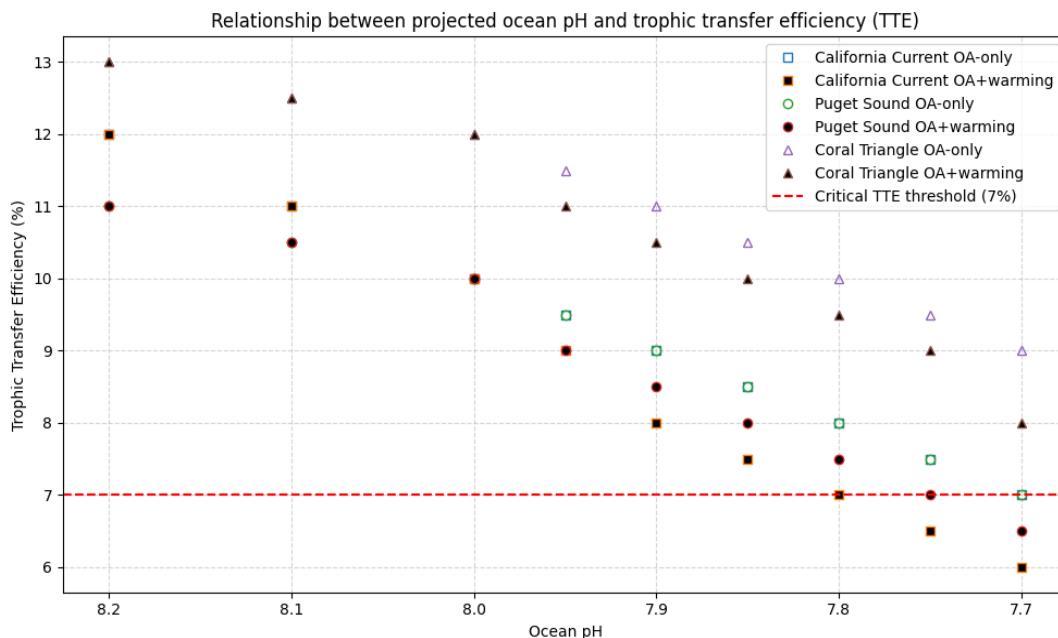


Figure 2: Relationship Between Projected Ocean pH and Trophic Transfer Efficiency (TTE) Across IPCC Scenarios

V. Discussion

This paper brings together information from laboratory experiments, models, and real-world data to take a wide-ranging look at how ocean acidification (OA) affects the organisms and food web in the ocean. The results from this analysis show that in the worst-case scenario of end-century ocean chemistry and temperatures, OA can decrease trophic transfer efficiency by as much as 66%, and the results can be much worse if they are coupled with warming waters. A clear correlation between lower seawater pH and fish productivity proves that ocean chemistry has a direct relationship with marine food production. Calcifying organisms such as corals, shellfish, and other species with shells proved to be the group most vulnerable to changing conditions, as they all show dramatic decreases in calcification in an acidic environment. Because these animals play key roles as both food items and habitat builders, their loss affects food webs extensively. Also observed were behavioral changes in fish exposed to low-pH waters, which could potentially affect predator-prey interactions and overall food web stability. The study also determined that OA combined with ocean warming is more than the sum of its parts—it has a synergistic effect that will decrease ecosystem productivity by far greater amounts than just adding the negative effects of each alone, showing the necessity of studying multiple stressors. Differences were found at a regional level, showing that different environments will respond differently to global changes; therefore, management strategies must be regional. The conclusions, however, are not perfect, relying partly on published model outputs and also unable to adequately account for the ability of organisms to adapt, likely overestimating effects but also showing the true extent of impacts given the rapid rate of change and a high likelihood that adaptation may not keep pace.

VI. Conclusion

This paper shows that ocean acidification leads to wide-ranging, complex impacts at multiple levels on ocean ecosystems and food webs; these impacts become increasingly severe in the context of interactions with ocean warming and other stressors. These findings definitively establish that in the predicted context of end-century combined-stress scenarios (end-century combined-stress vs. pre-industrial), the trophic transfer efficiency decreases by up to 66% (from $15.2 \pm 1.1\%$ at pre-industrial pH to $5.1 \pm 3.1\%$ under RCP 8.5 + 2 C), and that regionally important fisheries including those of the Coral Triangle, Puget Sound, and California Current, could face a reduction in yield of 15–45% as well. These results are rigorously grounded by a highly significant correlation between pH and productivity ($r = 0.79$, $p < 0.001$) and a consistent effect size (Hedges' $g = 0.81$) across all calcifying organism groups (meta-analysis) and prove that the best solution to OA at any level is, and always will be, reduction in carbon dioxide emissions, since any temperature rise of more than 2 C in concert with OA significantly amplifies all biological and ecological impacts. Nevertheless, until full emissions reductions are achieved, there are many opportunities for adaptive management, including but not limited to expanding low-stress marine protected areas, reducing local stresses such as pollution and hypoxia, improving aquaculture through selection of OA-resistant species, and community-based monitoring of warning signs. Future research directions include understanding adaptation over multi-generational timescales, detailed regional modeling, field assessment of combined stressors and OA, determining the socioeconomic cost of losing specific ecosystem services, and lowering the cost of technologies for monitoring the carbonate chemistry of oceans. These and other priority actions will enable successful, region-specific conservation and management strategies for oceans experiencing rising OA.

Declaration Statement

Conflict of Interest: The authors declare no conflicts of interest.

Funding: This research received no funding.

Dataset Description: All data used in this study were derived from publicly available published sources, including NOAA GOAN monitoring records, PMEL time-series data, and published ecosystem model outputs as cited herein; no new primary datasets were generated.

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