Going Once, Going Twice, and It's Gone:

The Effects of Ocean Acidification on Sea Urchin Larvae

Humans have always capitalized on the ocean as a source of food, from crustaceans to cephalopods to molluscs, there's something for everyone. One of many popular ocean delicacies is sea urchins. The globular bodies of sea urchins, which are marine invertebrates, are distinguished by their calcified spines (Gelman et al., 2022). There are over 800 species of sea urchins worldwide, but only 18 species are defined as edible (Zhou et al., 2018) (Figure 1). They are hand-harvested by scuba divers from the ocean coast for their gonads which are semi-circular shaped and orange-yellow in colour (Zhou et al., 2018). With their distinctive taste, sea urchin gonads (also termed "uni" or "roe") are often found at sushi restaurants or Asian grocers. The importance of sea urchins to the marine ecosystem can be observed through their integral role in the food web. Sea urchins are keystone species in marine ecosystems, and their role as the primary consumers of kelp forests dictate the abundance and distribution of kelp species (Gelman et al., 2022, Pfister & Bradbury, 1996). The alarming rate at which the oceans are acidifying affects the physiology of many calcifying marine organisms. Sea urchin larvae, however, are highly threatened due to differences in their development compared to other calcifying species.

Since the start of the industrial revolution, atmospheric carbon dioxide (CO_2) concentrations have risen at an abnormal rate (Jager et al., 2016) (Figure 2). At the same time, the ocean responds as a carbon sink to mitigate the excess CO_2 gas in the atmosphere. This absorption alters the ocean's carbonate chemistry and reduces the ocean's pH level (Jager et al., 2016; Havenhand et al., 2008) (Figure 3). Marine scientists coined this anthropogenic threat as ocean acidification (OA), which is the increased carbon dioxide dissolving into the ocean that instantly forms bicarbonate ions (HCO_3-), and at the same time, the release of hydrogen ions (Kerr, 2010). OA creates a chemical imbalance directly affecting marine sea life that relies on calcium carbonate to form and maintain its external skeletons/protective shells (González-Delgado & Hernández, 2018). Numerous investigations into the biological effects of OA on sea urchin larvae have shown that these effects negatively affect its populations in terms of calcification, growth, reproduction, and development (O'Donnell et al., 2009). Consequently, OA is interconnected with other environmental shifts like climate change and is accelerated by global warming. OA concentration levels are expected to double by 2100 (Havenhand et al., 2008), and thus it is crucial to understand how OA affects the growth and development of sea urchin larvae.

Similar to how many echinoderms and vertebrates develop, sea urchins reproduce by releasing eggs directly into seawater which are immediately fertilized by sperm (Hinegardner, 1969). Despite millions of larvae produced, only a handful reach adulthood beyond the plutei (larval) stage (Hinegardner, 1969). Sea urchins are most vulnerable at the plutei stage since they are extremely sensitive to seawater pH changes and have not fully developed a protective calcite skeleton (Stumpp et al., 2013). A study by Havenhand et al. (2008), reported an 11.7% reduction in sperm swimming speed and a 16.3% reduction in sperm motility as a result of increased ocean acidity, thus concluding acidification of ocean waters reduces the fertilization success of sea urchin larvae.

Just like humans, sea urchin larvae require optimal living conditions to thrive. Various studies have been carried out to understand the development of larval sea urchins in response to OA stressors. For instance, interactive effects of climate change stressors were observed in *Tripneustes gratilla* larvae. Brennand et al. (2010) conducted a study in the Southeast Australia climate change hot spot where the temperatures and acidification have increased significantly faster than the global average (+3˚-6˚C; —0.3-0.5 pH (acidification)) (Figure 4). The researchers found that while sea urchin larvae development accelerated in +3 ˚C water up to the threshold of +6˚C, larval calcite growth was impaired by increased water acidification. This demonstrates that increased temperatures, to an extent, can counteract the effects of OA but eventually, global warming and the rise in ocean water temperatures will still affect the calcification process in sea urchin larvae dissolving their shells in low-pH seawater.

Another study by Stumpp et al. (2013) focused on the effects of sea urchin larvae's gastric pH when placed in acidifying water conditions. Researchers used ion-selective micro-electrodes to measure the stomach pH of sea urchin larvae (Stumpp et al., 2013). Initial results found that the larvae's stomachs are naturally alkaline at a pH of ~9.5 aiding in kelp digestion as plant chloroplasts are more efficiently digested at higher pH than at acidic or neutral pH (Stumpp et al., 2013). Sea urchin larvae with chronic exposure to low pH showed delayed development and reduced somatic growth (Stumpp et al., 2013). Additionally, gastric pH levels decreased by 0.3-0.5 units, suggesting that larvae stomach alkalinity cannot be maintained in lower pH seawater (Stumpp et al., 2013) (Figure 5). Overall, the study found that due to low pH, there was a decreased digestive efficiency resulting in compensatory feeding. In other words, sea urchin larvae have to use energy-consuming methods such as growing longer arms to increase their feeding compared to larvae living in a higher pH environment.

In contrast to larvae's increased morphological size, studies have also found that the physiological development of the larval endoskeleton is affected by OA. O'Donnell et al. (2010) study on the skeletogenesis of *Lytechinus pictus* revealed a stunted or slower rate of development (Figure 6). Smaller larvae size meant that they could be preferentially preyed upon, and the duration of the larvae stage meant that sea urchin larvae are subjected to predators. This increased vulnerability in the larval stage increases the probability of offspring failing to reach adulthood. Similar to the study mentioned above, the authors also found that OA is linked to a decrease in larval metabolic activity reducing the productivity of skeleton formation, including decreased length of the skeleton.

Based on current research, sea urchin larvae interactions among OA, food availability and ecological variability are complex counterintuitive biological responses. This is evident by different inferences drawn from laboratory settings versus field settings. Additionally, the conflicting sea urchin larval sizes from Brennand et al. and O'Donnell et al.'s study makes it difficult to conclude OA effects. While marine scientists have stated that OA is reversible, it is highly unlikely that efforts made today will completely reverse the effects of acidification on marine species (Logan, 2010, Kleypas & Yates, 2009). According to marine ecologists, it will take hundreds of thousands of years to see results and it is unclear if calcifying marine organisms can adapt to these changes. Fortunately, research efforts are underway in an attempt to reverse or at least curb the rate of OA.

One of the more well-known approaches to decreasing OA is setting CO_2 emissions goals. Previous climate change negotiations such as the United Nations Framework Convention on Climate Change and the Kyoto Protocol targeted greenhouse gas emissions but did not specifically differentiate between CO_2 emissions and other gases (Logan, 2010). Therefore, the German Advisory Council on Climate Change recommended reducing greenhouse gases and ensuring limited carbon dioxide emissions (Press Release, 2006). In comparison, the Monaco Declaration is based on an international panel of scientists' recommendations for policymakers to consider atmospheric CO_2 as a pollutant when making climate change negotiations (Logan, 2010). The Interacademy Panel Statement on Ocean Acidification (2009) states, “Even with stabilisation of atmospheric CO2 at 450 ppm, ocean acidification will have profound impacts on many marine systems. Large and rapid reductions of global CO_2 emissions are needed globally by at least 50% by 2050.” These are some of the recommendations made by scientists and environmental activists as a call to action for the government.

Another solution proposed is approaching OA with geoengineering. Given what we know, OA is the consequence of human activities, thus applying geoengineering as an anthropogenic solution might reverse OA. More specifically, climate geoengineering involves engineering the geographical environment to counteract the effects of changes in ocean pH (Logan, 2010). Several studies have examined artificial ocean alkalinization (AOA) as a means to increase ocean alkalinity. Currently, scientists have suggested deep-ocean sequestration and nutrient fertilization as potential solutions to mitigate OA, however, additional research is needed to determine if these methods do more harm than good.

Researchers have stimulated the use of alkalizing agents such as calcium carbonate to increase the ocean’s alkalinity boosting CO_2 uptake while decreasing OA (Feng et al., 2016). A 2000s study introduced The Carbonate-Dissolution Method in which CO_2-rich exhaust gases from fossil-fuel power plants are dissolved in seawater to produce a carbonic acid solution (Caldeira & Rau, 2000). The solution is applied to a carbonate mineral to form calcium bicarbonate which is then diluted in the ocean (Caldeira & Rau, 2000). This method efficiently neutralizes CO_2-acidity and converts CO_2 to a form that does not interact with the atmosphere (Caldeira & Rau, 2000). Further research is required to determine whether deploying AOA at a global scale is the most efficient method for mitigating OA effects.

Ultimately, alleviating OA stressors on sea urchin larvae would help ensure their survivability, impact as a keystone species for kelp, and a food source for other ocean species. Other calcifying organisms around the world would also benefit from increased pH sea waters.

References

Brennand, H. S., Soars, N. A., Dworjanyn, S. A., Davis, A. M., & Byrne, M. (2010). Impact of Ocean Warming and Ocean Acidification on Larval Development and Calcification in the Sea Urchin Tripneustes gratilla. *PLOS ONE*, *5*(6), e11372. https://doi.org/10.1371/journal.pone.0011372

Caldeira, K., & Rau, G. H. (2000). Accelerating carbonate dissolution to sequester carbon dioxide in the ocean: Geochemical implications. *Geophysical Research Letters*, *27*(2), 225–228. https://doi.org/10.1029/1999gl002364

Coral Reefs and Ocean Acidification on JSTOR. (n.d.). http://www.jstor.org/stable/24861028

Examining Ocean Acidification on World Oceans Day. (2016). U.S. Government Accountability Office. https://www.gao.gov/blog/2016/06/08/examining-ocean-acidification-on-world-oceans-day

Feng, E. Y., Keller, D. M., Koeve, W., & Oschlies, A. (2016). Could artificial ocean alkalinization protect tropical coral ecosystems from ocean acidification? *Environmental Research Letters*, *11*(7), 074008. https://doi.org/10.1088/1748-9326/11/7/074008

Gelman, Y., Kwong, E., & Murphy-Lavoie, H. (2022, August 8). *Sea Urchin Toxicity*. StatPearls - NCBI Bookshelf. https://www.ncbi.nlm.nih.gov/books/NBK536934/

González-Delgado, S., & Hernández, J. L. (2018). The Importance of Natural Acidified Systems in the Study of Ocean Acidification: What Have We Learned? *Elsevier EBooks*, 57–99. https://doi.org/10.1016/bs.amb.2018.08.001

Havenhand, J. N., Buttler, F. R., Thorndyke, M. C., & Williamson, J. E. (2008). Near-future levels of ocean acidification reduce fertilization success in a sea urchin. *Current Biology*, *18*(15), R651–R652. https://doi.org/10.1016/j.cub.2008.06.015

Hinegardner, R. (1969). GROWTH AND DEVELOPMENT OF THE LABORATORY CULTURED SEA URCHIN. *The Biological Bulletin*, *137*(3), 465–475. https://doi.org/10.2307/1540168

J. (2019, February 13). *Can you Kelp Me? The Purple Sea Urchin: A Tale of Destruction*. The Watershed Project. https://thewatershedproject.org/can-you-kelp-me-the-purple-sea-urchin-a-tale-of-destruction/

Jager, T., Ravagnan, E., & Dupont, S. (2016). Near-future ocean acidification impacts maintenance costs in sea-urchin larvae: Identification of stress factors and tipping points using a DEB modelling approach. *Journal of Experimental Marine Biology and Ecology*, *474*, 11–17. https://doi.org/10.1016/j.jembe.2015.09.016

Kerr, R. A. (2010). Ocean Acidification Unprecedented, Unsettling. *Science*, *328*(5985), 1500–1501. https://doi.org/10.1126/science.328.5985.1500

Kleypas, J. A., & Yates, K. K. (2009). Coral Reefs and Ocean Acidification. *Oceanography*, *22*(4), 108–117. http://www.jstor.org/stable/24861028

Logan, C. A. (2010). A Review of Ocean Acidification and America's Response. *BioScience*, *60*(10), 819–828. https://doi.org/10.1525/bio.2010.60.10.8

O'Donnell, M., Hammond, L. M., & Hofmann, G. E. (2009). Predicted impact of ocean acidification on a marine invertebrate: elevated CO2 alters response to thermal stress in sea urchin larvae. *Marine Biology*, *156*(3), 439–446. https://doi.org/10.1007/s00227-008-1097-6

O'Donnell, M., Todgham, A. E., Sewell, M. A., Hammond, L. M., Ruggiero, K., Fangue, N. A., Zippay, M. L., & Hofmann, G. E. (2010). Ocean acidification alters skeletogenesis and gene expression in larval sea urchins. *Marine Ecology Progress Series*, *398*, 157–171. https://doi.org/10.3354/meps08346

Partnership, T. I. (2009). *IAP Statement on Ocean Acidification*. https://www.interacademies.org/statement/iap-statement-ocean-acidification

Pfister, C. A., & Bradbury, A. (1996). Harvesting Red Sea Urchins: Recent Effects and Future Predictions. *Ecological Applications*, *6*(1), 298–310. https://doi.org/10.2307/2269573

Press Release. (2006). https://www.wbgu.de/en/service/press/press-release/meere-und-kuesten-durch-kohlendioxid-doppelt-bedroht

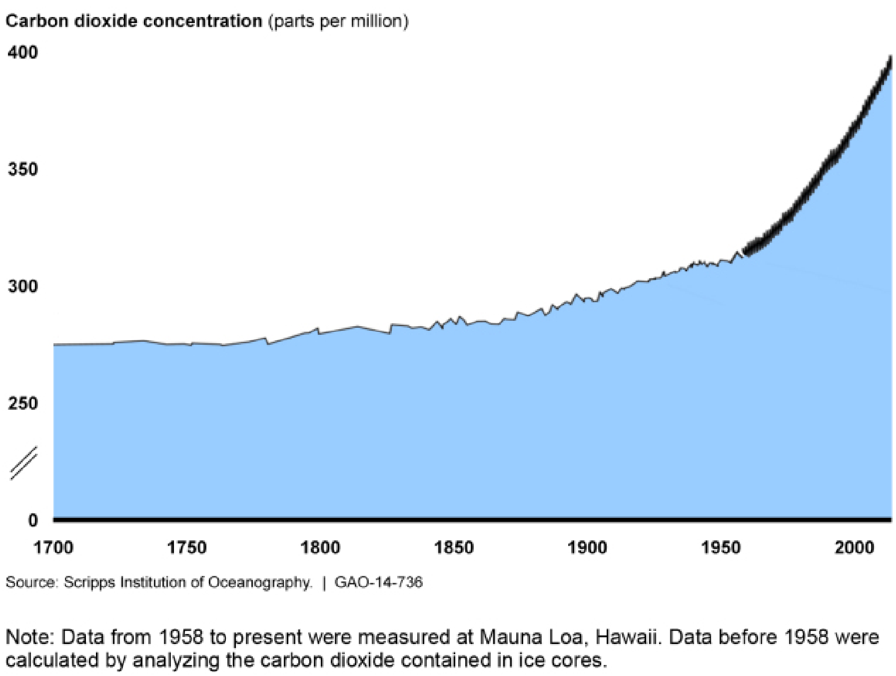
Stumpp, M., Hu, M. Y., Casties, I., Saborowski, R., Bleich, M., Melzner, F., & Dupont, S. (2013). Digestion in sea urchin larvae impaired under ocean acidification. *Nature Climate Change*, *3*(12), 1044–1049. https://doi.org/10.1038/nclimate2028

Zhou, X., Zhou, D., Lu, T., Liu, Z., Zhao, Q., Liu, Y., Hu, X., Zhang, J., & Shahidi, F. (2018). Characterization of lipids in three species of sea urchin. *Food Chemistry*, *241*, 97–103. https://doi.org/10.1016/j.foodchem.2017.08.076

Figure 1
Strongylocentrotus purpuratus, the purple sea urchin.

(Can you Kelp Me? The Purple Sea Urchin: A Tale of Destruction, 2019).

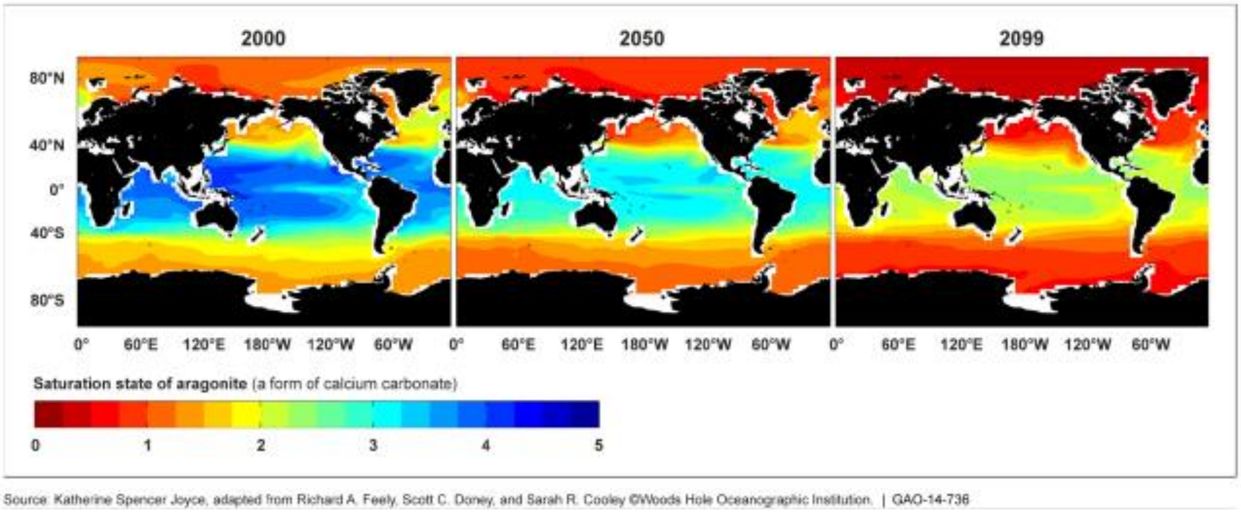
Figure 2
Atmospheric carbon dioxide concentrations, 1700-present.



(Examining Ocean Acidification on World Oceans Day, 2016).

Figure 3

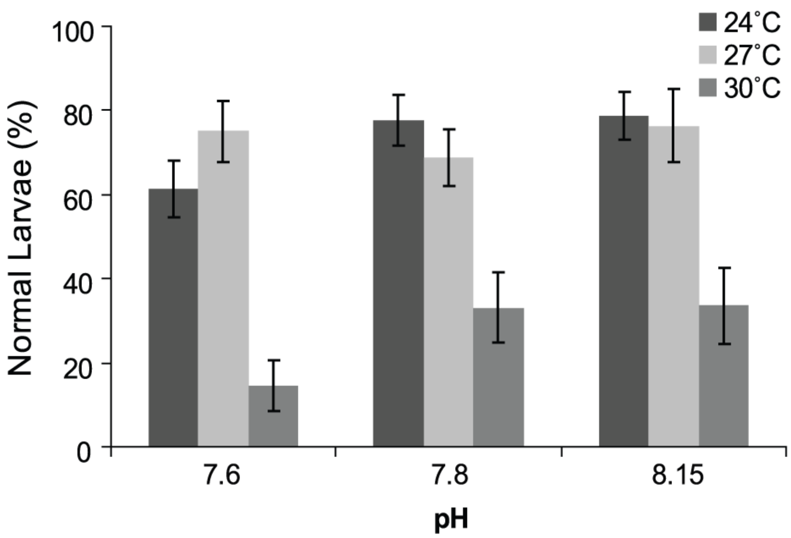
Current ocean pH saturation and predicated saturation levels in the future.



(Examining Ocean Acidification on World Oceans Day, 2016).

Figure 4

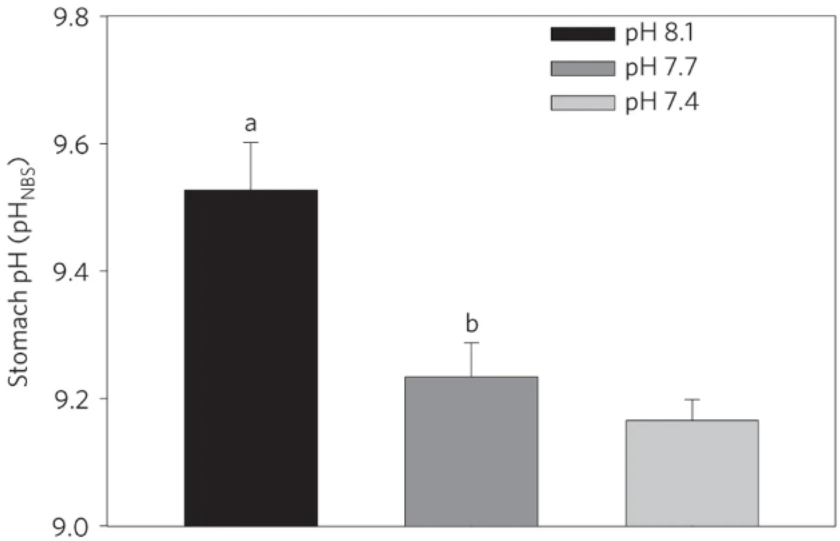
Percentage of normal T. gratilla larvae in nine treatments (3 pH×3 temperature levels) in the larvae from 3 females.



(Brennand et al., 2010).

Figure 5

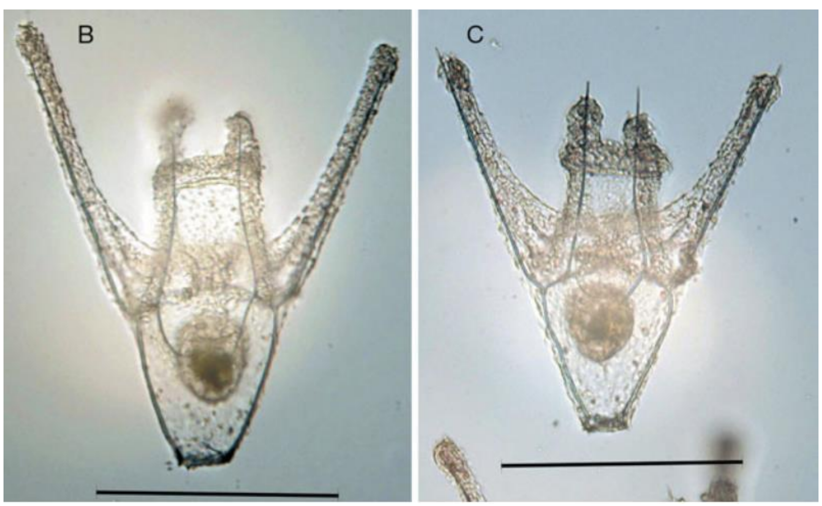
Effects of low pH water on sea urchin larvae gastric pH.



(Stumpp et al., 2013).

Figure 6

Morphological structure of sea urchin larvae. (b) representative larvae from control and (c) representative larvae in acidified seawater.



(O'Donnell et al., 2010).