

# Timing is everything: the effect of tidal timing on biodiversity during heatwaves

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## **Abstract**

Tidepool communities are highly vulnerable to ecological disturbances and serve as indicators of ecosystem health. A comprehensive understanding of tidepool response and recovery is crucial for assessing the long-term impacts of heatwaves on biodiversity and how these ecosystems respond. In this study, we examined how eight tidepools at Friday Harbor Labs, San Juan Island, WA, were impacted by a four-day heating event, where air temperature increased 5-10 °C above the mean monthly max normal. We surveyed biodiversity within pools before, three days, and eight days after the heatwave that took place from May 12th to May 15th. Coinciding with this heating period, a neap tide occurred, resulting in most of the observed pools being protected from exposure. Consequently, pools that remained submerged did not experience the adverse effects of increased air temperature. As a result, biodiversity did not change significantly over time. The pool at the highest elevation indicated no significant change in biodiversity during the heating event either— despite being exposed during the heatwave—likely due to its inhabitants being adapted for these stresses. This research highlights the importance of considering exposure and elevation in anticipating the effects of stress events on tidal communities.

## 1. Introduction

It is clear that the effects of global warming are accelerating (IPCC, 2021). What this means for marine ecosystems is projected increases in global atmospheric and oceanic temperatures, ocean acidification, oceanic deoxygenation, and increased frequencies of atmospheric and marine heatwaves (Cooley, 2022). As a result of these impacts, there are threats to marine life including loss of biodiversity, rapid extinction, altered reproduction, and geographic distribution which are expected to increase over time (Chen, 2011). Though not discussed as much as the effects of gradual temperature increases, anthropogenic climate change has been increasing the frequency of discrete atmospheric and marine heatwaves drastically and is predicted to accelerate in the future. The effects of these heatwaves often push organisms beyond their thermal stress limits, resulting in mortality (Laufkötter, 2020). These dangerous results of climate change are no longer just models of prediction and are already impacting entire ecosystems. The Pacific Northwest recently experienced a historically extreme heatwave in 2021, with various locations reaching temperatures more than 5°C greater than their historical records. This resulted in over one billion marine invertebrate mortalities in a period of around 2 days (White, 2023).

As extreme heatwaves are becoming more prevalent, it is extremely important to understand how they can affect biodiversity and individual species' health, as well as which factors might impact these outcomes. Knowing what ecological damages come as a result of a natural heating event is crucial knowledge as we brace for more frequent and extreme heatwaves to come. Because of this, we wanted to answer these questions directly through observational research. During our preliminary data collections on various tidepools at Friday Harbor Labs on San Juan Island, we learned of an upcoming heatwave, and anticipated there would be valuable data we could monitor and analyze before, during, and after this period.

The IPCC defines an atmospheric heatwave as a period of abnormally hot weather, often defined with reference to a relative temperature threshold, lasting from two days to months (IPCC, 2022). Between May 12 and May 15, the daily maximum temperatures at the Friday

Harbor Labs weather station ranged from 5 to 10 degrees Celsius above the mean maximum temperature normal for May (about 17.5 degrees Celsius).

Tidepools were chosen to be monitored before and after the heatwave because they are known to be strongly affected by disturbances, and tend to be indicative of how the ecosystem as a whole responds and restructures following a disturbance (Dethier, 1984). During a period of heating, organisms can undergo desiccation, bleaching, and thermal stress, resulting in relocation or mortality of many individuals (Zhou, 2022). Our goal was to monitor and compare the species richness (the number of species present) and abundance (the number of individuals of each species) before and after a disturbance event in various pools to understand its effects on biodiversity. We then looked at factors specific to each tidepool that might dampen or amplify the effects of this disturbance. In our research, we recorded data on species richness and species abundance among motile and sessile species both before and after the heatwave. Before, during, and after, we monitored abiotic factors such as pH, salinity, water temperature, and atmospheric temperature. Collecting this data, we aimed to monitor species richness, species abundance, and their relationships to the temperature of the air and the tidepools, as well as the time since the heatwave occurred. However, the dates of the heatwave happened to coincide with a neap tide, resulting in a lack of exposure for most of the tidepools we were monitoring during those hotter periods. As a result, the tidepools were protected from the detrimental effects that heatwaves are known to have on intertidal life and we failed to see any significant changes in biodiversity.

The questions we wanted to answer were how intertidal ecosystems in tidepool microhabitats would respond to and potentially recover from the heatwave over the following days. We also asked whether there was variation between the responses from the various pools, and which factors might influence that. We anticipate that similar to previous heatwaves, pools that are exposed during the heatwave will have a decrease in overall species abundance and will have fewer dominant species taking over during recovery from the high temperatures, thus decreasing species richness and overall biodiversity. We anticipate that the pools which are at lower elevations and not exposed during the heating event will not show significant differences in species abundance and richness from before and after the heating period.

## 2. Materials and Methods



**Fig. 1. Field site and tide pool locations.** (A) Location of field site in Friday Harbor, San Juan Island. (map from National Geographic viewer [public domain]). (B) Tide pool range (n=8) along the rocky intertidal at varying elevations. (C) Representative tide pool quadrat. Quadrats were placed randomly and algae abundance was quantified by percent coverage.

Our research was conducted along the rocky shore below Friday Harbor Labs on San Juan Island (48.549186 °N, -123.006622 °W). Abiotic data was collected from May 5 to May 23, and full quadrat surveys were conducted on 5/11, 5/18-19 (referred to as 5/18 in figures for simplicity), and 5/23. Eight clearly defined tidepools were selected in the intertidal based on size, depth, intertidal height, volume, and prevalent species. Tidepools were located within a rocky intertidal area (Fig. 1B) stretching 0.21 kilometers from tide pool 1 to tide pool 8. Tidepool locations ranged from low to high intertidal, with elevations falling between 1.11 ft and 5.75 ft above mean lower low water (MMLW). Elevation was calculated using a CST/Berger® stadia rod and hand level. For each pool, we measured or calculated surface area, volume, maximum

depth, and perimeter. Surface area and perimeter were calculated using ImageJ software, and volume was approximated as surface area multiplied by average depth (approximated by averaging 10 randomized depths across each pool).

On May 6th we attached waterproof Onset® Hobo® data loggers to the bottom of each tide pool using Z-spar® epoxy, and set them to record data every fifteen minutes. Air temperature data was sourced from the FHL scientific weather station at Cantilever point. On days abiotic data was collected, we used a Fluke® 26 gun thermometer to measure water surface temperature, a SunGrow® salinity meter to measure pool salinity, and Fisherbrand® pH meter to calculate the pH of each pool by averaging across 3 different areas.

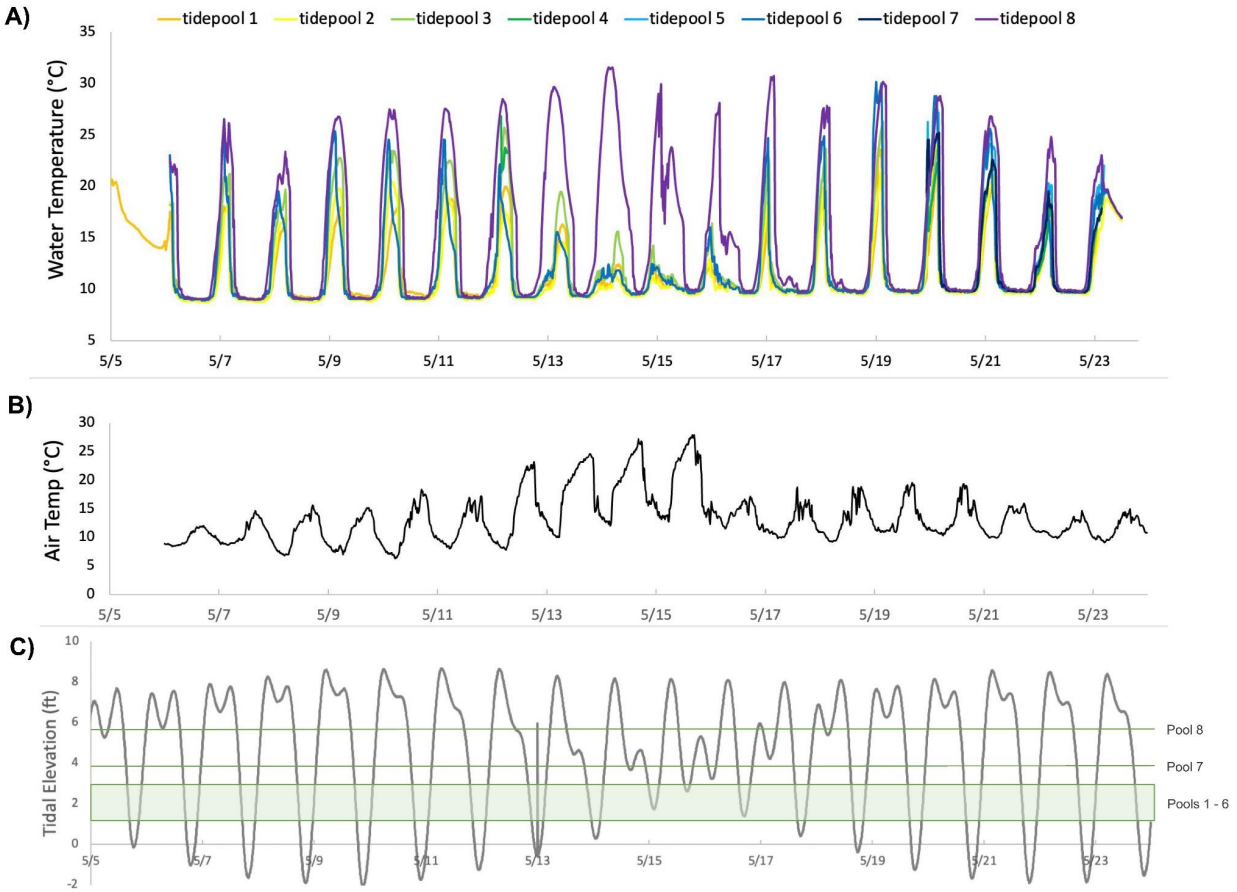
To determine species richness (the total number of spp. in each pool) and relative abundance, species were categorized as sessile (algae and barnacles, recorded by percent cover) or motile (inverts and sculpins, recorded by count). Abundance and percent coverage were calculated using 25 x 25 cm quadrats (Fig. 1C). The number of quadrats per pool ranged from 2-6, relative to the surface area of each tidepool. Quadrats were randomly placed to approximate species coverage within the entire pool, and the minimum percentage cover assigned to a species in any quadrat was 4%. The three days of data collection were chosen for their proximity to the heating event to monitor biodiversity before the event, the immediate days following, and eight days after the event to understand recovery. Time was used as our metric for air temperature.

We used non-metric multidimensional scaling to analyze how environmental variables influenced differences in species abundance among the pools over time. Species percent cover data was averaged over quadrats for each pool and organized into a "species matrix" showing percent abundance for each species (n=45), for every pool on 3 different quadrating days (n=24). Abiotic data was similarly arranged into an "environmental matrix" showing pH, salinity, surface temperature, volume, and elevation for every pool on the three survey days (Kindt, 2005). In order to visually quantify differences among pools based on relative species abundance and abiotic factors we ran an NMDS using the R package BiodiversityR. NMDS was chosen over other ordination techniques because it is well suited to abundance data and does not make assumptions about linearity or equal variance (Holland, 2021). R calculated the Bray-Curtis

ecological distance between trials (8 sites on 3 days) and produced a graphic (Fig. 5A) for 2 axes based on 20 random restarts, with a final stress value of 0.17. We also used the env.fit function to superimpose abiotic factor vectors onto the NMDS and visualize the relative importance of environmental variables in contributing to the spread among the samples. Vectors were also produced to show the relative importance of the statistically significant species, contributing to the spread.

Biodiversity was calculated for each pool using the inverse of the Simpson index,  $1/D$ , where  $D = [\sum n_i (n_i - 1)] / (N(N - 1))$ ,  $n_i$  is the number of individuals in the  $i$ -th species and  $N$  is the total number of individuals in the community. For  $n$ -values, we used abundance data averaged over all the quadrats for a sampling day in each given pool. All statistical analyses were performed using the R statistical software R 4.3.0.

### 3. Results

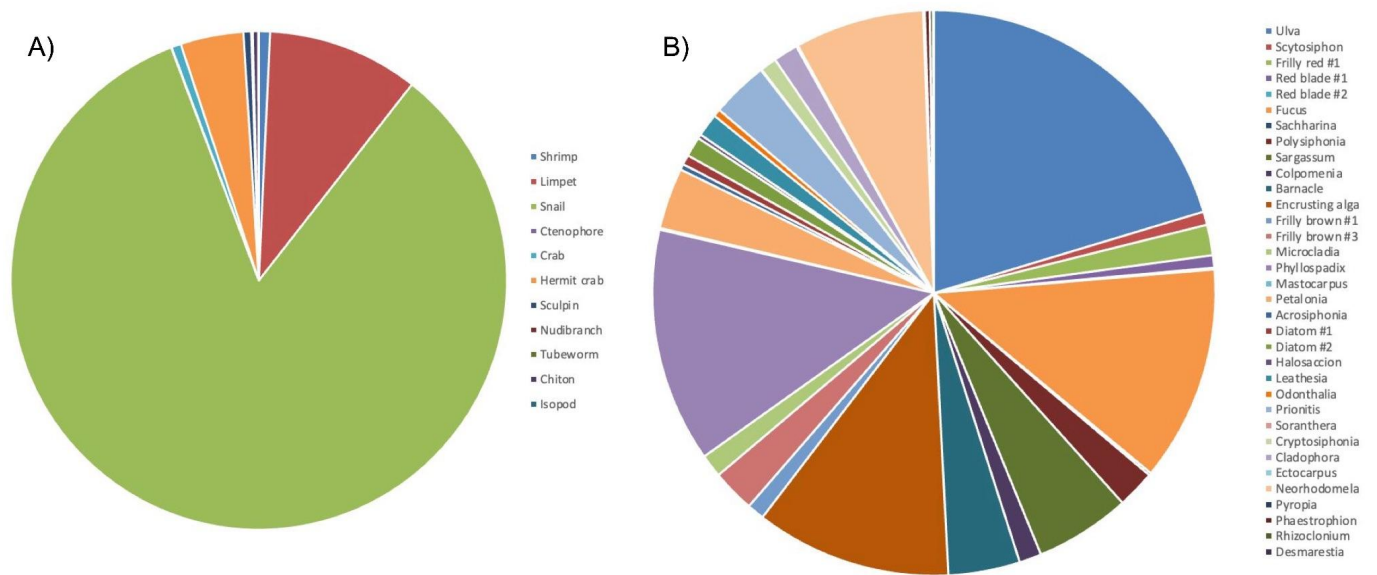


**Fig. 2. Water temperature, air temperature and tidal elevation at Friday Harbor Labs from 5/5 to 5/23.** Quadratting was done on May 11th, 18th, and 23rd. (A) Tidepool temperature in °C over time showing that pool 8 was the only one to experience heating from 5/13 to 5/16. (B) Air Temperature in °C over time in Friday Harbor, WA [FHL Weather Station] (C) Tidal elevation in feet over time [NOAA Tide Predictions]. A neap tide occurred from approximately 5/13 to 5/16. The green box indicates the elevations of pools 1-6. Green lines represent elevations of pools 7 and 8, which have a significantly higher elevation, influencing how they were affected by the heatwave.

Our data for temperature, tidal elevation, and air temperature helps us understand how our tidepools responded to the heatwave. Data loggers in each pool showed temperature fluctuations each day (Fig. 2A). During the heating period (5/12-5/15), tidepool 8 was affected by temperature significantly. Tidepool 8 is at a higher elevation than any other selected pool at a height of 7'7.5" above MLLW. During this heating period and the days following, we also experienced a neap tide (Fig. 2C). A neap tide occurs seven days after a spring tide, where high tides are lower than average and low tides are higher than average, creating a less drastic transition between high and low tide ("...Spring Tides", n.d.). During the neap tide, low tide

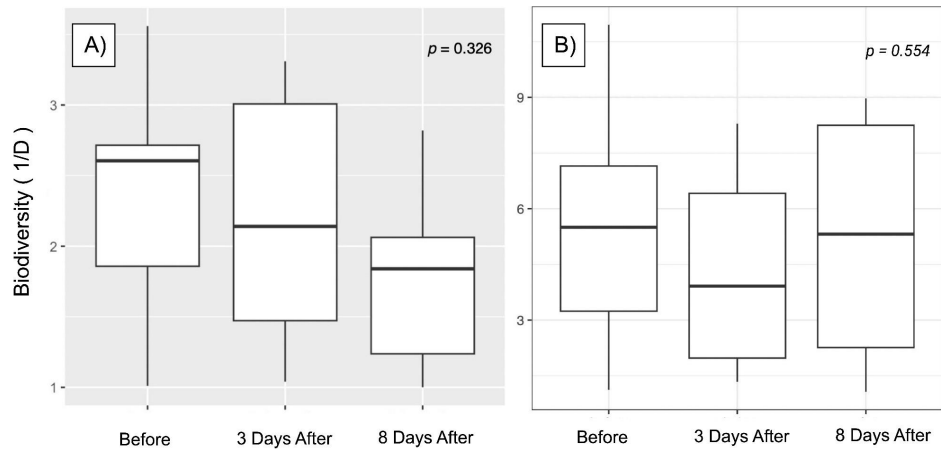
reached 2 ft above MLLW. Our lowest tidepool is at a height of 1.11ft above MLLW. As a result, most of our tidepools remained submerged, preventing them from heating. With the exception of pool 8, the neap tide resulted in the coldest tidepool water temperature experienced throughout our study.

We identified 45 species across our eight observed pools. Dominant sessile organisms included *Ulva sp.*, *Fucus distichus*, and *Neorhodomela* as well as the angiosperm *Phyllospadix scouleri* (Fig. 3A). Snails were the most prevalent animals in our pools, followed by limpets and hermit crabs (Fig. 3B). Throughout our entire study, tidepool 1 had the greatest species richness (R=24) and tidepool 8 had the least species richness (R=6) on May 23 (Table 2).



**Fig. 3. Tide pool species compositions.** (A) Relative abundance (counts) of motile species. (B) Relative abundance (% cover) of sessile species. Algae we were unable to identify were given names (e.g. red blade #1) and photographed so they could be identified on later quadratting days. Diatom #1 and #2 refer to macroscopic tube-dwelling diatom colonies.

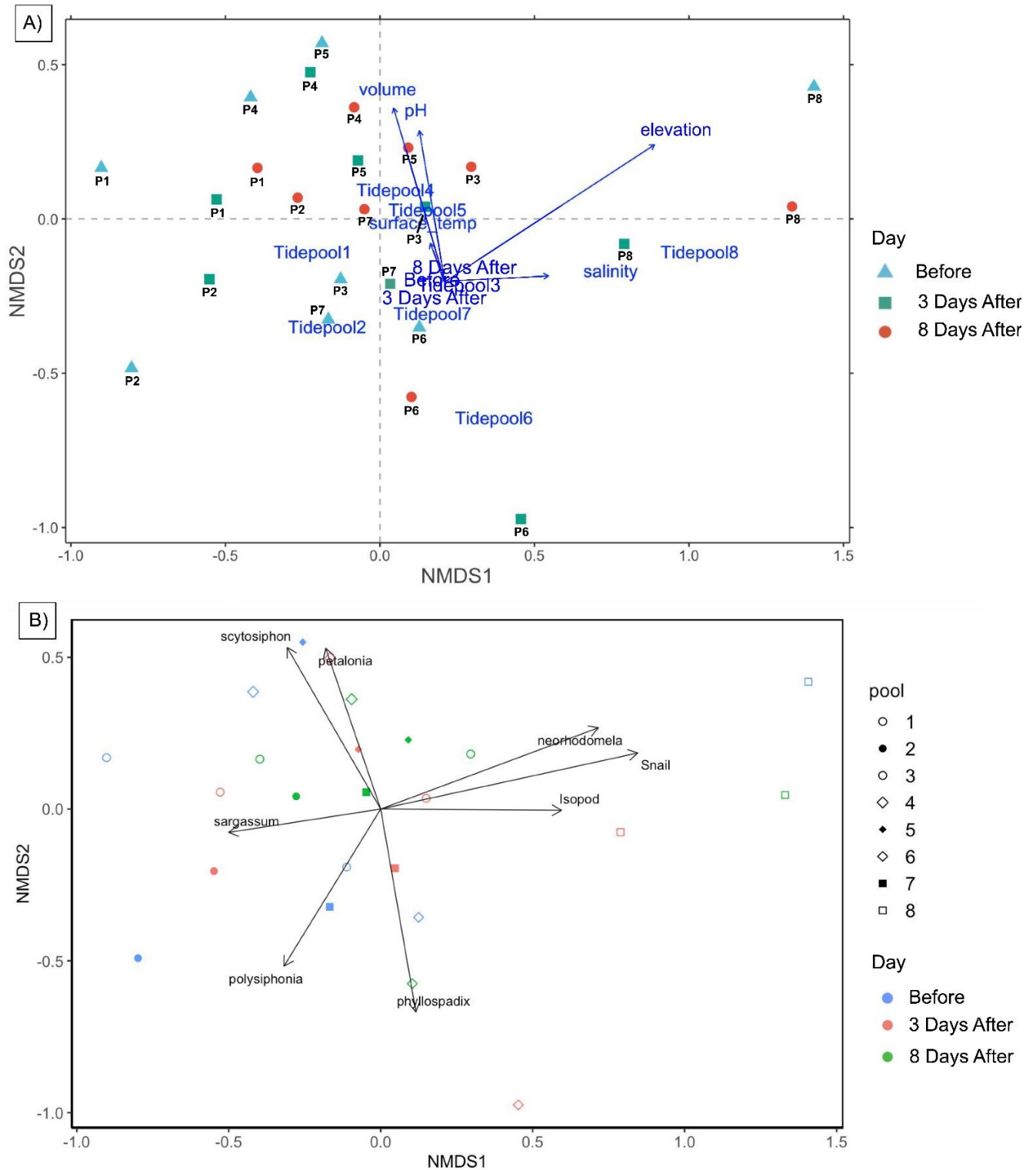
Sessile and motile species were analyzed separately because sessile species were measured for percent cover while motile species were measured by count. Sessile organisms include red algae, brown algae, green algae, *Phyllospadix scouleri*, diatoms, and encrusting algae. Motile organisms included snails, limpets, crabs, chiton, shrimp, and other invertebrates.



**Fig. 4. Boxplots showing changes in biodiversity (1 / Simpson's diversity index) over the study period. (A) Motile species biodiversity over time. Each box shows data for n = 8 pools. X-axis labels are relative to the heatwave. There was a tendency for biodiversity to decline with time, but biodiversity did not respond to significantly to the heatwave ( $p = 0.326$ ). (B) Biodiversity in sessile species over time. There was a tendency for biodiversity to decrease and return back to normal levels with time, but biodiversity did not respond to significantly to the heatwave ( $p = 0.554$ ).**

We found that there was no correlation between time and species diversity for sessile and motile species over the duration of the heating event. Motile species (Fig. 4A) did not respond significantly ( $p = 0.236$ ). Sessile species (Fig. 4B) also had no significant response ( $p = 0.554$ ). If biodiversity is not affected by time, it is by extension unaffected by atmospheric temperature.

In our NMDS, we recognized a statistical significance of environmental factors in only our elevation and volume with respective p-values of 0.001 and 0.013 (Fig. 5A). The p-values for the other variables were as follows: pH,  $p = 0.06$ ; salinity,  $p = 0.26$ ; surface temperature,  $p = 0.80$ . Our p-values for our statistically significant species (Fig. 5B) were: *Scytosiphon*,  $p = 0.016$ ; *Petalonia*  $p = 0.025$ ; *Neorhodomela*  $p = 0.0003$ , *Sargassum*  $p = 0.046$ ; *Polysiphonia*,  $p = 0.011$ ; *Phyllospadix*,  $p = 0.005$ ; snails,  $p = 0.001$ ; and isopods,  $p = 0.020$ .



**Fig. 5. Non-metric multi-dimensional scaling ordinations (NMDS).** A) Points represent the average quadrat per pool (P1 = tide pool 1) each sampling day (see legend). Vectors of environmental variables are fitted to the ordination showing relative importance. Of the five environmental variables, only volume and elevation were significant. B) Vectors show the 8 statistically significant species ( total # spp. = 45) and how they contributed to spread among the pools.

We conducted a two-tailed paired t-test on tidepool species abundance from the first and the last day of data collection in pool 8. Our results of 45 species (df = 44) provided a t-stat of -0.99499. The p-value was far higher than 0.05, preventing us from rejecting the null hypothesis (p = 0.325181). Tidepool 8 did not have a significant change in species abundance.

|                              | Biodiversity Before | Biodiversity 8 Days After |
|------------------------------|---------------------|---------------------------|
| Mean                         | 4.010667            | 5.558667                  |
| Variance                     | 709.7402            | 1374.704                  |
| Observations                 | 45                  | 45                        |
| Pearson Correlation          | 0.999994            |                           |
| Hypothesized Mean Difference | 0                   |                           |
| df                           | 44                  |                           |
| t Stat                       | -0.99499            |                           |
| P(T<=t) one-tail             | 0.162591            |                           |
| t Critical one-tail          | 1.68023             |                           |
| P(T<=t) two-tail             | 0.325181            |                           |
| t Critical two-tail          | 2.015368            |                           |

**Table 1. Paired t-test showing Tidepool 8 Simpson's biodiversity before and after the heating event.** Tidepool 8, the only pool exposed during the heating event, showed no significant difference in biodiversity before and after heating.

|                            | Pool | Richness | Simpson's Sessile | Simpson's Motile |
|----------------------------|------|----------|-------------------|------------------|
| <i>Before (5/11)</i>       | 1    | 14       | 6.54              | 2.71             |
|                            | 2    | 15       | 8.98              | 2.69             |
|                            | 3    | 12       | 6.11              | 2.52             |
|                            | 4    | 21       | 10.96             | 1.93             |
|                            | 5    | 17       | 3.7               | 3.56             |
|                            | 6    | 11       | 1.86              | 1.64             |
|                            | 7    | 13       | 4.89              | 2.73             |
|                            | 8    | 7        | 1.12              | 1.01             |
| <i>3 Days After (5/18)</i> | 1    | 17       | 8.29              | 2.68             |
|                            | 2    | 13       | 4.95              | 1.6              |
|                            | 3    | 19       | 6.23              | 1.49             |
|                            | 4    | 21       | 6.97              | 3.31             |
|                            | 5    | 13       | 2.88              | 3.09             |
|                            | 6    | 5        | 1.43              | 1.42             |
|                            | 7    | 11       | 2.16              | 2.98             |
|                            | 8    | 9        | 1.34              | 1.04             |
| <i>8 Days After (5/23)</i> | 1    | 24       | 8.39              | 1.96             |
|                            | 2    | 17       | 8.2               | 2.28             |
|                            | 3    | 19       | 5.94              | 1.27             |
|                            | 4    | 20       | 8.97              | 1.99             |
|                            | 5    | 16       | 4.69              | 1.72             |
|                            | 6    | 8        | 1.63              | 1.14             |
|                            | 7    | 14       | 2.47              | 2.82             |
|                            | 8    | 6        | 1.07              | 1                |

**Table 2. Species richness and biodiversity.** Richness is the number of species per pool. Simpson's Sessile and Motile are the reciprocal of Simpson's Diversity index for sessile species (% cover data) and motile species (count data).

#### 4. Discussion

Due to the severity of the neap tide that overlapped with the heating period, only one of our pools (tidepool 8) was exposed to the atmosphere during the hottest days of our study. From the data we collected, parts of our hypothesis were supported, and other parts were not.

First, it was interesting to analyze the abiotic and biodiversity data pool 8 provided throughout the heating period, especially when compared with all of the other pools, as pool 8 was the only tidepool exposed during the hottest periods of the heatwave. Tidepool 8 had the highest elevation by a wide margin—the next closest pool was tidepool 7 which was around 0.8m lower. It also had the lowest biodiversity by a large margin throughout our study. Despite exposure, very little changed in species richness over time. There were 8 ( $\pm 2$ ) species present in the entire pool during each collection indicating that there was very little shift in the species present as a result of heating. This data does not support our hypothesis, as we expected species richness to decrease significantly if exposed during the disturbance event. Our hypothesis also lacked support from our data in the results of species abundance over time. Though we expected species abundance to decrease throughout the heating, we recognized no significant differences between species abundance before and after the heating. In fact, there was a slight increase in species abundance.

We believe these data findings are a result of a high-elevation tidepool, whose ecosystem is adapted to high heat stress and desiccation. The pools at higher elevations will be exposed for a higher percentage of the time. They will only sometimes be below the tidal height, resulting in a microhabitat with high stress on the organisms within. The organisms dominant in pool 8 were *Neorhodomela sp.* and its commonly associated invertebrate *Littorina sp.* (Choi, 2006). It is documented that both of these species can withstand high levels of desiccation and disturbance (Raymond, 1993) (Mahanes, 2022), and this is likely the reason for their dominance in the tidepool with the highest elevation we recorded; *Neorhodomela* was not seen in any other pool. In other words, this pool and its ecology were prepared for the effects of the heatwave and were not altered much by it as a result.

Some of our hypotheses were, however, supported by the data we collected. As we predicted, there was a lack of significant changes in biodiversity among the tidepools that were not exposed during the heatwave. Using Simpson's Diversity Index, we could not reject the null hypothesis expressing that there was no significant change in biodiversity across data collections. This lack of change in biodiversity is important to note, especially when compared to how pools might respond when exposed during a heatwave. We predict that had the pools at lower elevations been exposed during the disturbance event, we would have seen trends more similar to our hypotheses. The species dominant in these pools are not adapted to the high levels of thermal stress and desiccation that they likely would have encountered if exposed. This might have decreased species abundance and richness, and biodiversity as a result.

Across the intertidal zonation, biodiversity changes. Where there is more access to water, oxygen, and nutrients as well as less heat and disturbance stresses, there is higher biodiversity. Often, this is the case at the lower intertidal (*Intertidal Zone*, 2022). Tidepools generally provide species some of these benefits including cooler temperatures, as well as oxygen and nutrients replenished consistently by the tides; they also lack the abrasion and wave exposure that the lower intertidal species might face. As heat intensity or time exposed above the tide increases, more stress is put on the biota within the pools. This can kill life in the pools, and eventually lead to a dominance of species more adapted for those environments, as seen in pool 8. Because the remainder of our pools were not exposed above the tides on the hottest days of the heatwave, they were sheltered from many of these stressors and did not face drastic relocation of motile species or mortality.

Elevation was not the only significant factor in our tidepools. Our NMDS indicated that there was a significant correlation with the volume of pools as well. Our observational data shows that Tidepools 1 and 4 were both among the top three highest biodiversity indices throughout the study as well as the top 3 greatest volumes of pools. Though this is a relatively unexplored relationship in current ecological studies, it is possible that larger tidepools tend to host greater biodiversity as there could be fewer environmental stresses which can inhibit the variety of species present.

Our study has provided valuable information in ecology about the effects of heatwaves, neap tides, and their concurrence on tidepool habitats. An examination of the species richness, species abundance, and biodiversity among the variety of tidepools that we observed highlights the protective nature of the higher tides on intertidal ecosystems, as there was great consistency in these factors despite the presence of a disturbance event. Our study also points out the importance of elevation as a factor in influencing ecological adaptation in dominant species, as we saw certain species most dominant in tidepool 8 that weren't seen nearly as prevalent in the lower intertidal. The species which were dominant in this pool were those that were best adapted to high heat, which is why they were able to withstand the disturbance event without much change in biodiversity by any metric over time.

There is still much research to be done in this sector of ecology which can improve our understanding of environmental patterns that will become more frequent and severe as global warming continues to accelerate. We recommend that research be done on the relationship between tidepool biodiversity and their volumes, as our data show a potentially significant correlation between these factors. Research regarding tidepool biodiversity across intertidal zonation is also surprisingly limited and should be conducted to determine what species, how many species, and how many individuals in each species can be seen in pools at varying tidal elevations. One important study to be conducted which would provide much insight into where our study was limited is one with more exposed tidepools during a heatwave. A replicated observational study with tidepools at lower elevations fully exposed to heatwaves can support or oppose our prediction that biodiversity should decrease as a result of exposure at lower tidal elevations. In the future, there will be situations where this occurs, potentially being detrimental to intertidal ecosystems as a whole.

#### *Sources of error:*

Some potential sources of error may have impacted our results. Our experiment did not account for other changes in the environment, such as rain, which can influence salinity. We also did not account for any predation and consumption of sessile and motile species. If a predator or

consumer were to prey upon any of the species within a pool, it would reduce the biodiversity and abundance of said species. Therefore, if biodiversity did decrease over time, we would have no way of knowing whether or not it was the heatwave or predation that reduced the biodiversity and abundance within each respective tidepool. Some species (exclusively motile species) are also much more migratory than others, and thus their habitat is not limited to a single tidepool. Some of the species that we counted within the tidepool may have been temporary visitors and weren't representative of the actual biodiversity of each tidepool. Our tidepools were also not protected from outside interference by other students, visitors, or faculty members, and any disturbances made by said individuals could have impacted our data. Other physical disturbances could have included excess wave action brought about by nearby boats or weather conditions that displaced motile species.

## **5. Acknowledgments**

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## 7. Appendix

Species Abundance:

<https://docs.google.com/spreadsheets/d/e/2PACX-1vQr9Xa3Y5PI0iDpmTKXlZnlmtT6iiFcJbP293Yf--5itHT3fUI3RDW35MX001dAfYMXuxRNT0qVv2CX/pubhtml>

Environmental Data:

[https://docs.google.com/spreadsheets/d/e/2PACX-1vTpVEFHQOe5TvpU-5v9O2EdJR6q5yBZFuFIlyDiWpG77k2d1VWPvv3e3-VU1a8H\\_tXsczRyzoeQ3VN/pubhtml](https://docs.google.com/spreadsheets/d/e/2PACX-1vTpVEFHQOe5TvpU-5v9O2EdJR6q5yBZFuFIlyDiWpG77k2d1VWPvv3e3-VU1a8H_tXsczRyzoeQ3VN/pubhtml)