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Hawai'i Climate
Utilizing NASA Earth Observations to Assess Thermal Stress Impacts on Coastal Hawaiian Fishponds

DEVELOP Technical Report
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Raz Wachtel (Project Lead)
Danielle Sonobe
Tyler Morgan
Mina Nada

Advisors:
Christine Lee, PhD, NASA Jet Propulsion Laboratory, California Institute of Technology (Science Advisor)
Kelly Luis, PhD, NASA Jet Propulsion Laboratory, California Institute of Technology (Science Advisor)
Angelica Rodriguez, PhD, NASA Jet Propulsion Laboratory, California Institute of Technology (Science Advisor)
Benjamin M. Holt, M.S., NASA Jet Propulsion Laboratory, California Institute of Technology (Science Advisor)

Lead:
Michael A. Pazmino, M.S. (California – JPL)

1. Abstract

Hawaiian fishponds (loko i'a), ancient aquaculture systems created over 1500 years ago, historically served to harvest prized native fish species. Colonization-induced changes in land management have reduced active loko i'a from over 500 to ~20, destabilizing nearshore ecosystems and diminishing native Hawaiian cultural traditions. In recent decades, efforts to restore loko i'a have intensified as part of a broader emphasis on preserving Hawaiian cultural identity. Anthropogenic-induced climate change threatens these systems, particularly through the increase in frequency and magnitude of marine heatwaves. Though largely unexplored, these events are effectively studied utilizing remote sensing via Earth observations. Leveraging this technique enables autonomous extraction of water quality parameters to inform fishpond management. This study examined seven loko i'a across the main Hawaiian Islands (Hawai'i Island, Moloka'i, Maui, O'ahu, Kaua'i). Sea surface temperature and normalized difference chlorophyll index measurements were derived in fishponds utilizing Landsat 8 Thermal Infrared Sensor Thermal Infrared Sensor and Sentinel-2 MultiSpectral Instrument between 2013 to 2023, while regional patterns in temperature and chlorophyll-a were observed via Aqua's Moderate Resolution Imaging Spectroradiometer (2002–2021). Employing these sensors, we focused analysis around the 2015 and 2019 marine heatwaves in the Pacific. We observed a heat stress gradient across the archipelago, creating thermally sheltered and unsheltered fishponds, yet identified no notable localized relationships between temperature and chlorophyll-a. Additionally, we applied pre-determined thermal maxima for culturally significant fish species (Striped Mullet: *Mugil cephalus*; Milkfish: *Chanos Chanos*) to assess historical habitat suitability within fishponds. While the direct impacts of marine heatwaves on loko i'a ecology are unknown, temperature patterns observed in this study are cause for concern.

Key Terms

Remote Sensing, Earth Observations, Indigenous Science, Sea Surface Temperature, Chlorophyll-a, Hawai'i, Conservation, Marine Heatwave

2. Introduction

2.1 Background Information:

Many native fish species are experiencing population declines due to degradation of habitats with changing environmental stressors (McCoy et al., 2017). In the Pacific Islands, specifically Hawai'i, indigenous culture emphasized self-sufficiency and sustainability of the environment in stewardship of both land and ocean systems (Kagawa et al., 2012). Aquaculture in Hawai'i was historically dominated by networks of fishponds, of which five distinct categories exist under different design principles: loko i'a kalo (freshwater taro), loko wai (freshwater), loko pu'uone (brackish water), kuapa (seawater), and loko 'umeiki (fish traps; Costa-Pierce, 1987; Kikuchi, 1976). Together, these fishponds can be described by loko i'a, as an umbrella term (Kikuchi et al., 1976; Keala et al., 2007; Lowe, 2004). Loko i'a exist as both nearshore and inland fisheries where they often mimic estuarine systems, as fresh water meets the ocean to mix and create a unique water composition within a walled pond. They often include common native fish species such as the 'ama 'ama (striped mullet) and awa (milkfish), historically prized for consumption, which utilize these areas for predation, shelter, and reproduction (Tabandera, 2019). Maintenance of the ecological stability of loko i'a can help ensure Hawaiian food security, as these areas have historically provided up to 2 million pounds (~907184 kg) of fish catch per year (Keala, 2007; Cobb, 1905). Consequently, restoration projects can bolster inshore marine ecosystem stability, increase community engagement in cultural practices and provide mass economic growth in fishery output (Lowe, 2004; Keala et al., 2007).

Loko i'a and inshore fisheries in Hawai'i are threatened by climate change (Lowe, 2004; Lyles, 2016; Kamala, 2018). Correlations have been drawn between increasing water temperatures and fish mortality within loko i'a (McCoy et al., 2017). While few remote sensing studies have been conducted on the ramifications of ocean warming in loko i'a, extensive literature documenting its effect on Hawaiian coral reefs exists (Xu et al., 2020;

Caldwell et al., 2016; Ma et al., 2023). Our project is the first study of its kind to assess feasibility applications of NASA Earth observations in studying climate related effects on loko i'a. To complete our regional analysis, we established an arbitrary boundary extent around the major Hawaiian Islands and surrounding Pacific Ocean (coordinates: [-153.63514], [-153.63514], [-160.66639], [-160.66639]). However, the lack of historical data complicates how we discern these areas' response to changing climate trends and past marine heatwaves. The novel use of Landsat 8 Thermal Infrared Sensor (TIRS) and Sentinel-2 Multispectral Instrument (MSI) sensors to monitor targeted loko i'a provides a means to derive past sea surface temperature data, chlorophyll-a concentrations and turbidity levels — key parameters potentially detrimental to localized ecological equilibrium.

2.2. Project Partners and Objectives:

We were able to effectively observe temporal and spatial changes in and around loko i'a by drawing data from multiple satellite sensors at varying resolutions. Previous studies have employed similar techniques: moderate resolution sensors such as Landsat 8 TIRS (30-meter resolution) and Sentinel-2 MSI (10-meter resolution) have been used to study habitat suitability of Delta Smelt in the San Francisco Estuary in response to warming waters (Halverson et al., 2022) and monitor water quality parameters such as Chlorophyll-a and turbidity in both small, inland water bodies and coastal areas (Yang et al., 2023), respectively. Additionally, lower resolution sensors, namely Aqua's Moderate Resolution Imaging Spectroradiometer (MODIS; 4.6 km resolution), have provided a means to evaluate thermal stress for coastal environments and coral bleaching events (Putra et al., 2019). Utilizing these sensors, we created a buffer zone around the seven loko i'a across the archipelago (Hawai'i Island, Maui, Moloka'i, O'ahu, Kaua'I; Figure 1). Our objective was to examine the feasibility of determining the extent and effect of the 2015 and 2019 Pacific Marine Heatwaves at both regional and localized scales using water quality metrics derived from publicly available satellite data, with the hopes of informing community-managed loko i'a stewardship organizations of future viable restoration projects.

We partnered with three organizations: Kua ʻĀina Ulu ʻAuamo (KUA), the National Oceanographic and Atmospheric Administration (NOAA) Pacific Islands Regional Office, and the University of Hawai'i at Manoa (UHM). KUA is a nonprofit organization based in Hawai'i aimed at promoting ʻāina momona, the health of ecological systems in Hawai'i that enhances community and cultural wellness, utilizing community-based management of natural and cultural resources. Using this study's findings, KUA will apply them to their restoration efforts as they begin to locate new sites for fishponds. Researchers at NOAA and UHM provided subject expertise, guiding the focus of the project. Bridging academic, government and non-profit partner collaboration, we aimed to make public NASA Earth observations accessible to partner organizations and promote open science by demonstrating their utility to advance the field of ecological conservation.

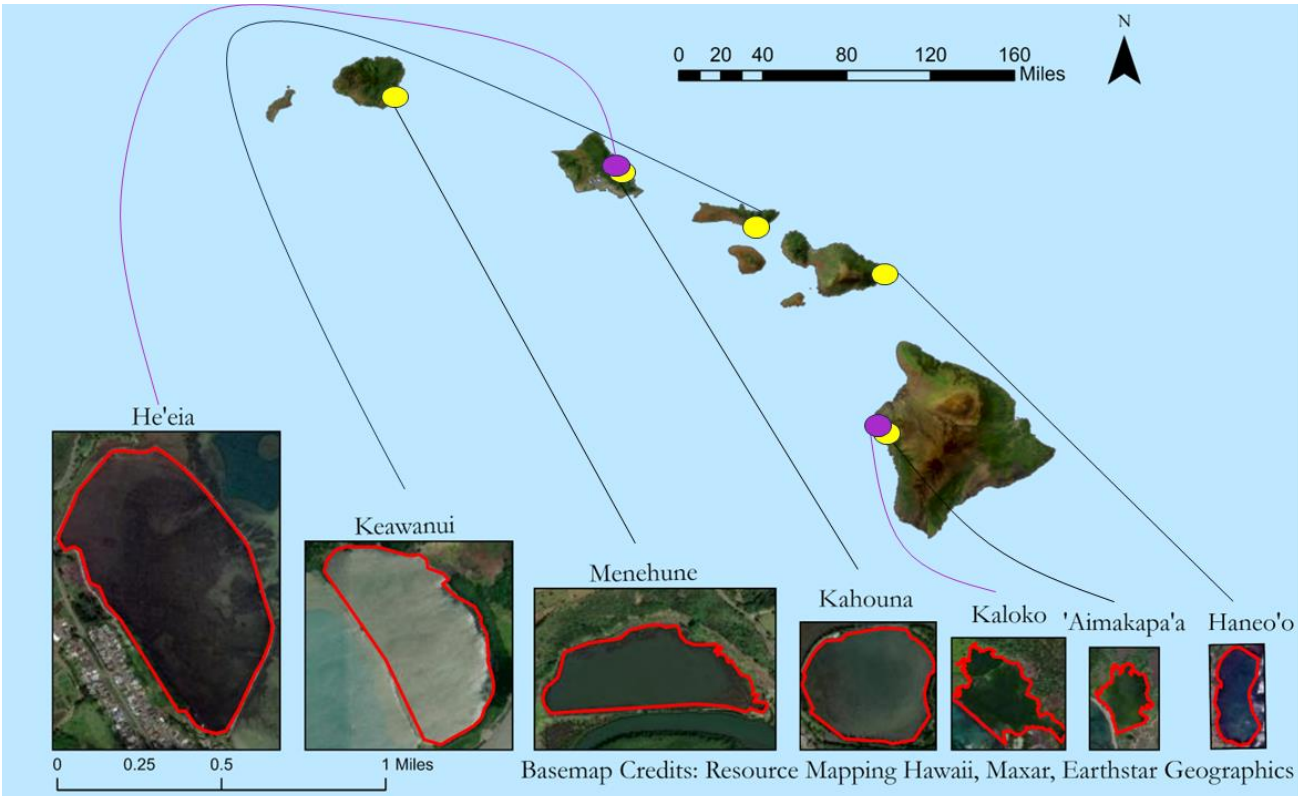

Figure 1. Study area: Coastal fishponds within the main Hawaiian Islands. Heʻeia (O'ahu), Kahouna (O'ahu), Menehune (Kaua'i) and Keawanui (Moloka'i), 'Aimakapa'a (Hawai'i Island), Kaloko (Hawai'i Island), and Haneo'o (Maui). Ponds maps all use the same scale bar and are drawn to represent their true sizes compared to one another. The main Hawaiian Islands use a separate scale bar denoted by increments shown at the top of the map. Ponds are ordered from largest to smallest surface area from left to right. Different colored points and lines are used to visually distinguish nearby ponds on the same island.

3. Methodology

3.1 Data Acquisition

We acquired multispectral imagery from Google Earth Engine's (GEE) data catalog through the GEE JavaScript API for Landsat 8 TIRS (2013 – 2023), Sentinel-2 MSI Level 2A (2019 – 2023) and Aqua MODIS (2002 – 2021; Table 1). We utilized the full temporal range of Landsat 8 TIRS and Sentinel-2 MSI, and the available processed data for Aqua MODIS, to comprehensively assess the occurrence and potential anomaly of heatwaves, particularly focusing on the notable events of 2015 and 2019. This approach allowed us to discern temporal trends and ascertain whether these events were exceptional occurrences or recurrent phenomena over the study period. The complete historical data archive from each deployed satellite mission was analyzed to determine if the observed marine heatwaves in 2015 and 2019 were locally anomalous. We extracted regional sea surface temperature (SST) and Chlorophyll-a concentration data within the predefined bounding box encompassing the Hawaiian Islands.

Our partner, KUA, provided existing loko i'a locations (n=30) as a shapefile. Data cleaning to redraw their boundaries to match modern coastlines was completed in ArcGIS Pro, and the updated shapefile was used in our analyses. We chose a representative sample of 7 coastal ponds with the largest surface area across multiple islands: Heʻeia (O'ahu), Kahouna (O'ahu), Menehune (Kaua'i) and Keawanui (Moloka'i), 'Aimakapa'a (Hawai'i Island), Kaloko (Hawai'i Island), and Haneo'o (Maui).

Table 1.
Earth Observation Information

Earth Observation	GEE Image Collection ID	Parameter	Resolution	Timeframe
Sentinel-2 MSI	COPERNICUS/S2_SR_HARMONIZED	Chlorophyll-a	10 m	2019-2023
Landsat 8 TIRS	LANDSAT/LC08/C02/T1_L2	SST	100 m	2013-2023
Aqua MODIS	NASA/OCEANDATA/MODIS-Aqua/L3SMI	Chlorophyll-a & SST	4.6 km	2002-2021

3.2 Data Processing

3.2.1 Atmospheric Correction / Cloud Masking

Within GEE's JavaScript API, we utilized two separate cloud masks, optimized for different sensors. For Landsat 8 TIRS, we applied a pre-existing cloud mask that filtered out pixels using the quality assessment bands "QA_PIXEL" and "QA_RADSAT", excluding non-zero values indicative of cloud reflectance and shadows based on saturation. For Sentinel-2 MSI, we employed GEE's pre-existing cloud mask "QA60" for the same purpose, effectively eliminating clouds from our images.

3.2.2 Water Quality Parameters

We gathered monthly SST data from Aqua MODIS "Ocean Color SMI: Standard Mapped Image MODIS Aqua Data" between August 2002 to December 2021 then we calculated median values from the "sst" band. Then, we combined all pixels within our regional extent boundary, encapsulating the main Hawaiian Islands and parts of the Pacific Ocean, into a timeseries animation showing monthly values. Because this data product from Aqua MODIS is a level 3 product, all acquired data was preprocessed and therefore did not require additional cloud masking. The same methods were also applied within the 15-mile buffer shapefile to gather average chlorophyll-a and SST values over coastal areas.

We extracted Landsat 8's TIRS collection 2, level 2, tier 1 band data as a single band and converted raw band integers into degrees Celsius temperature values. We calculated the average water temperatures, omitting the outer 70 m region of the pond to avoid recording temperatures of combined land and sea pixels. Similarly, we extracted Harmonized Sentinel-2 MSI collection level 2, tier 2 data, using two bands from the dataset to calculate an estimate of chlorophyll-a. We utilized the Red Edge 1 (B5) and Red (B4) bands to calculate chlorophyll-a values through a previously defined normalized difference chlorophyll index (NDCI) equation (Mishra and Mishra, 2012):

$$(1) \qquad NDCI = \frac{(RedEdge\ 1 - Red)}{(RedEdge\ 1 + Red)}$$

In this regard, NDCI serves as an indicator of aquatic biomass, particularly pertinent given the shallow nature of the ponds. This metric encapsulates chlorophyll-a levels within the water column and biomass, including algae and seagrass, on the pond floor as maximum depths does not exceed 3 meters. Sentinel-2 MSI chlorophyll-a values were calculated as a median value per fishpond and stored identically to Landsat 8 temperature values, but the outer 10m area of each pond shape was omitted from the median instead of the outer 70m area of data. We did this to avoid measuring land chlorophyll-a estimates mixed with our pond water chlorophyll-a estimates and take advantage of the more precise resolution available with Sentinel-2 MSI imagery which was able to distinguish pixels closer to the edge of the pond better than our TIRS data could.

3.3 Data Analysis

3.3.1 Water Quality Parameters

We utilized Aqua MODIS (2002 – 2021) and Landsat 8 TIRS (2013 – 2023) SST data to visually identify geographical locations and periods of notable, anomalous heat events stress around the main Hawaiian Islands. In response to an apparent "island shadow" exhibited in the imagery, we categorized loko i'a to either be "sheltered" (located outside the island shadow on the eastern side of the islands with less exposure to greater temperatures) or "unsheltered" (located on the west side within the island shadow and exposed to consistently higher ocean temperatures). We categorized areas of consistently low heat stress or regional sheltering as shapefiles and considered for more thorough analysis.

We calculated the average Landsat 8 SST of each pond over time and visualized each in a time series and aggregated them based on the sheltered or unsheltered proximity classifications. We also compared the overall spread of temperatures between ponds, ordered by size, and divided into rainy season (November to April) or dry season (May to October) observations to fit best within the context of seasons appropriate for Hawai'i (Lu et al., 2020). Emphasis was placed on SST values during the 2015 and 2019 marine heatwaves to assess any apparent outliers within our results.

We visualized Sentinel-2 MSI chlorophyll-a values in identical time series and boxplots to the Landsat 8 temperature visuals. In the analysis, we considered pond size, season, and heatwave events as potential correlative factors. Additionally, we used these visuals to qualitatively explore patterns in chlorophyll-a among the seven ponds.

3.3.2 Loko I'a Ecology: Habitat Suitability Analysis

We conducted a thermal habitat suitability analysis on selected ponds to evaluate their viability for juvenile ama and 'ama 'ama survivability. We then visualized the thermal thresholds of the juvenile fish at 16 °C minimum and 33 °C maximum. We approximated these thresholds from prior studies on ama, based on their ability to move from larval to juvenile stages (Chang et al., 2016; Villaluz, 1981), and included them in quantitative thermal timeseries charts derived from Landsat 8 TIRS in each of the selected study sites.

4. Results & Discussion

4.1 Analysis of Results

4.1.1 Regional Thermal Stress

To investigate the regional patterns in thermal stress over the main Hawaiian Islands, we scanned Aqua MODIS SST imagery for patterns denoting geographic sheltering, or relatively cool coastal regions that remained stable throughout the year. Aqua MODIS SST maps showed a pattern of dynamic temperature differences surrounding the state of Hawai'i (Figure 2). For example, average highest temperatures during 2016 show the main islands' southwest side was predominantly warmer, while the northeast side was typically cooler (Figure 2). Many circulation considerations likely contribute to this surface temperature distribution, such as advection by large-scale currents and surface heat fluxes. For example, the archipelago is a known barrier to the westward-flowing North Equatorial Current (Lumpkin, 1998; Azevedo Correia de Souza et al. 2015), leading to complex flow patterns and eddy generation as the current bifurcates around the island chain. Given that all but one of the fishponds examined in this study directly front the coast, SST patterns observed during heatwaves in this regional area indicate similar impacts on the ponds themselves.

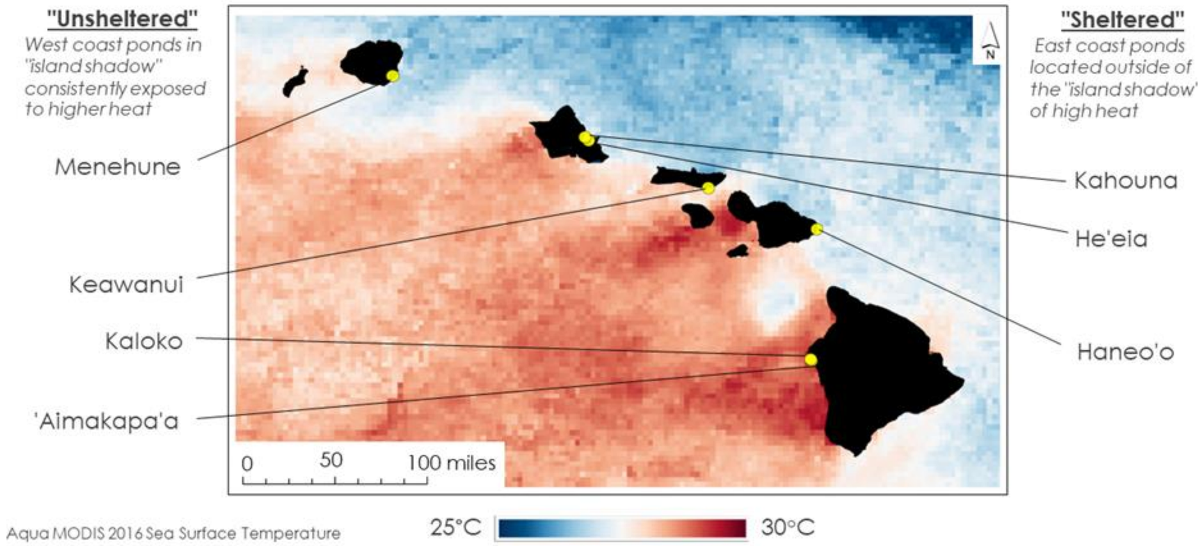

Figure 2. Study area map overlaid on Aqua MODIS imagery of 2016 average sea surface temperature indicating the seven selected ponds, and where each was located with approximate sheltering mechanisms visible for each to justify classification.

Of our seven selected ponds, we empirically categorized four southwestern loko i'a as 'unsheltered' and three eastern coast ponds as 'sheltered' (Figure 2). When examined on an annual basis, the protective effect of the 'sheltered' ponds appeared to diminish in periods of elevated stress, particularly noticeable during the 2015 and 2019 marine heatwaves (Figure 3). Annually, peak ocean temperatures (2013 – 2021) generally occurred in September and October, accompanied by a notable SST gradient between the west and east coasts of the Islands. However, during 2015 and 2019, years marked by marine heatwaves, the distinction in this gradient is reduced, with both coasts experiencing elevated SST (Figure 3).

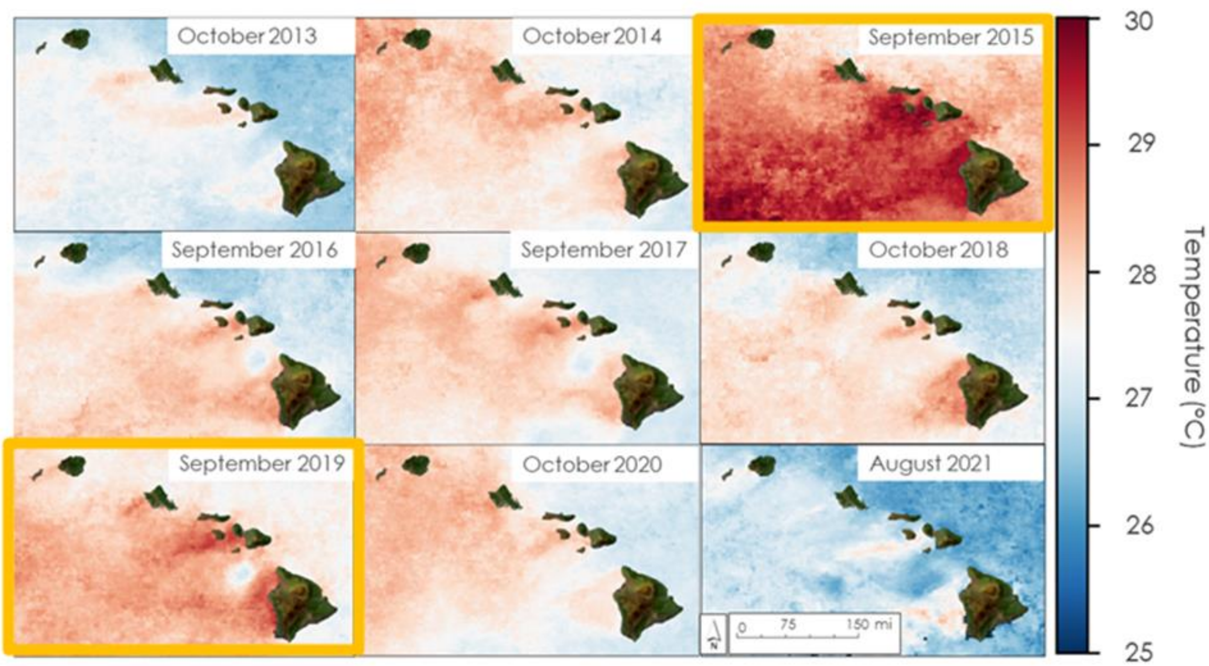

Figure 3. MODIS Aqua Imagery maps showing the average surface temperature of the hottest months of each year between 2013 and 2021. Yellow bounding boxes indicate marine heatwaves.

4.1.2 Internal Loko i'a Patterns
Unsheltered ponds seemed to sustain relatively higher temperatures, frequently exceeding the juvenile awa and ‘ama ‘ama thermal maxima of 33 °C, particularly in the case of the two smallest loko i’a, Kaloko and ‘Aimakapa’a (Figure 4a). On the other hand, Menehune and Keawanui were more consistent, showing temperatures that aligned with sheltered loko i’a. The sheltered fishponds maintained average temperatures below the thermal threshold for juvenile fish mortality, with exceptions noted in 2014 and 2018 when certain months saw temperatures surpassing this threshold. All sheltered loko i’a. had similar temperature ranges and seasonal cycles to one another.

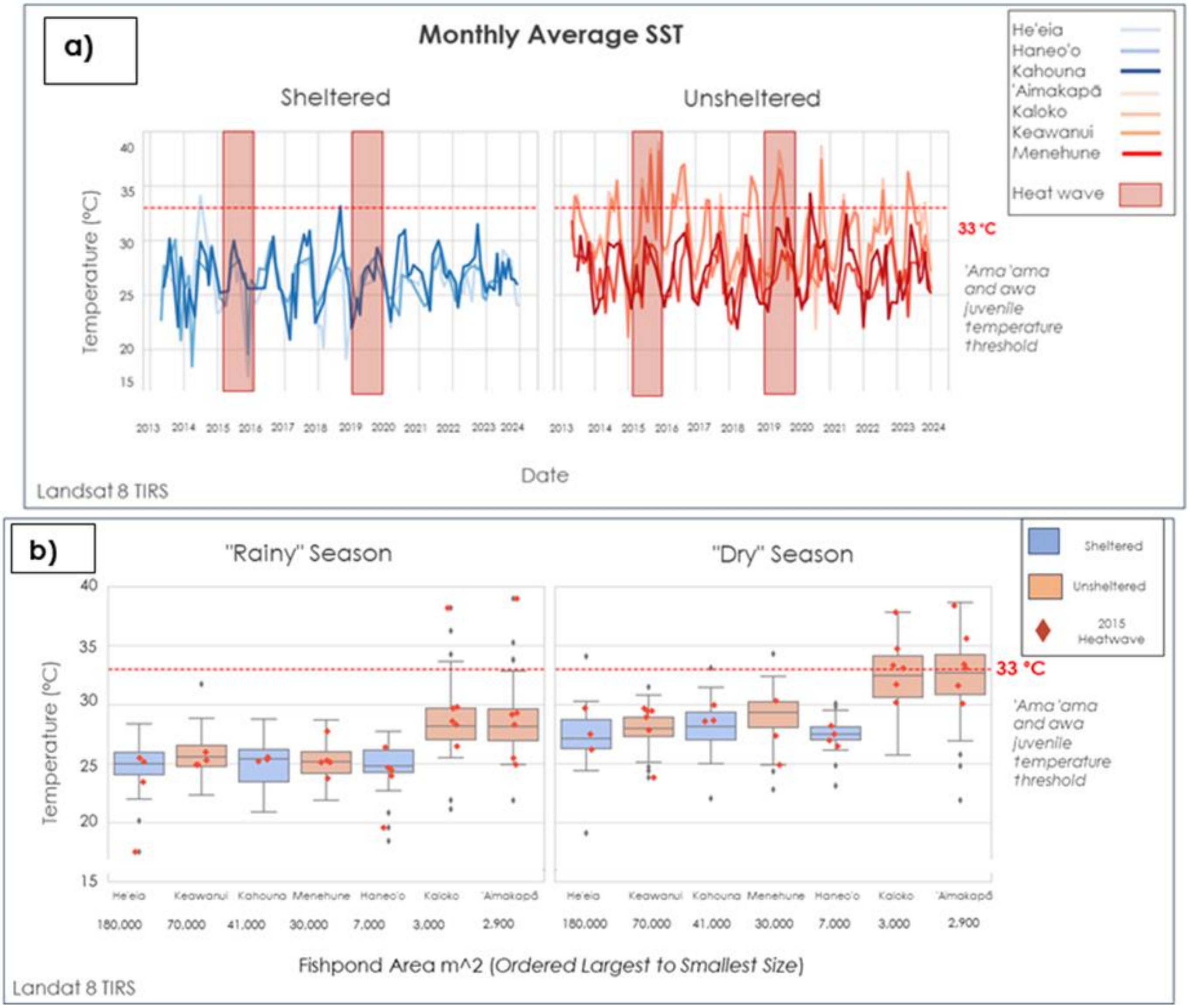

Figure 4. (a) Time series of average water surface temperature within each pond from 2013 to 2023. Ponds were classified as sheltered or unsheltered from heat stress depending on approximate coastal location on east coast or west coast, respectively. Light red shaded regions highlight the 2015 and 2019 Pacific marine heatwaves. (b) Boxplots of monthly average temperature values throughout both rainy and dry seasons (2013 – 2023). Red dots (diamond in legend) indicate values recorded during marine heatwave periods. Dotted lines in both figures represent the approximate thermal maxima of juvenile awa and ‘ama ‘ama before mortality occurs.

Additionally, temperature ranges within these ponds differed noticeably between rainy (November to April) and dry seasons (May to October; Figure 4b). Rainy seasons generally showed lower temperatures than their dry season counterpart. In the rainy season, sheltered and unsheltered ponds experienced similar temperature ranges, excluding the two smallest ponds, Kaloko and ʻAimakapa'a. The dry season showed clearer patterns: sheltered ponds tended to have lower values, while unsheltered ponds tended to exceed maximum sheltered pond temperatures. Furthermore, smaller ponds generally noted higher average temperatures regardless of their sheltered or unsheltered state.

We conducted a similar exploratory data analysis for chlorophyll-a, expecting that sheltered, cooler ponds would have higher average NDCI than unsheltered, warmer ponds. However, when grouped, sheltered and unsheltered ponds showed only marginal differences in NDCI values, perhaps slightly higher in unsheltered areas (Figure 5a). Menehune observed a sharp decline in NDCI values between 2019 – 2021 and did not return to its initial NDCI value; most other ponds oscillated within a similar range, with variable seasonal cycles from pond to pond. When split into rainy and dry seasons, a larger range of NDCI values was observed during the rainy season, with additional parameters of pond size and sheltering showing little difference in average chlorophyll-a levels (Figure 5b).

Figure 5. (a) Time series of average chlorophyll-a, measured by the normalized difference chlorophyll index, within each pond from 2019 to 2023. Ponds were classified as sheltered or unsheltered from heat stress

depending on approximate coastal location. (b) Boxplot of all monthly average chlorophyll-a values observed in each pond during rainy and dry seasons between 2019 and 2023.

Gaining a mechanistic understanding of loko i'a and their relationships with both their local environment and the nearby ocean is critically important to elucidating the role marine heatwaves play in affecting their health. Remote sensing functions as an effective tool to observe regional patterns across these environments and is an important first step in quantifying proximate ocean and pond water quality parameters. Augmented by future *in situ* data collection, this methodology points to improvements in comprehensive research initiatives, such as predictive modelling of aquatic ecosystem resilience and responses to climate extremes, including marine heatwaves.

4.2 Feasibility for Partner Use

4.2.1 Errors and Uncertainty

While our analysis of thermal sheltering mechanisms may be useful in understanding the direct impacts of marine heatwaves, it is important to note the lack of available ground truth data and other viable estimates of land surface temperature within these localized regions. Specifically, there was little capacity to provide essential ground truthing data for temperature, turbidity, and chlorophyll-a for any fishponds. With further investigation, there is potential to utilize buoys or work more closely with partners to achieve this.

Likewise, remote sensing via NASA Earth observations presents its own set of challenges, namely cloud cover and spatial and temporal resolution. Landsat 8 TIRS's and Sentinel-2 MSI's respective temporal spacing of observations of 16 and 10 days made it difficult to compute reliable temperature averages at the monthly level, particularly when data collection was distorted by heavy cloud cover, a common condition during the rainy season. Using satellite imagery with a higher revisit period would enable more comprehensive, cloud free images to be utilized.

To isolate key impacts from the marine heatwave, a comprehensive understanding of fishpond productivity (observed as chlorophyll-a) and how that productivity interacts with temperature and the habitat is necessary. Given that maximum loko i'a depths did not exceed 2-3 meters, it is important to consider that the chlorophyll-a measurements obtained from NASA Earth observations may include contributions from photosynthetic activity in the benthic zone, providing another source of error. Additionally, while the ponds we examined were on the land-ocean boundary and likely interacted with the local ocean, the impact of this interaction compared to groundwater input and local land usage is largely unknown. For example, it is possible that ponds assumed to be unsuitable based on ocean temperature dynamics alone are maintained at tolerable levels for fish from cooler groundwater, or vice versa. Moreover, the absence of fish abundance data poses challenges to our analysis. In situ data comparisons are a next step for concretely relating heatwave stress and native fish species.

4.2.2 Methodology Practicality and Partner Engagement

NASA Earth observations excel at measuring regional climactic phenomena and were useful in helping to identify large-scale sheltering mechanisms in this study. When moving towards a more thorough investigation of loko i'a, remote sensing is optimally utilized and understood when coupled by in situ or drone estimated water quality parameter measurements (Cheng et al., 2020; Lee et al., 2016). It is important that our partners combine our resources with their own knowledge of loko i'a systems. Due to the absence of in situ data concerning water quality parameters, our understanding of the variability and suitability of loko i'a was constrained. A more extensive multiyear investigation, coupled with in situ data collection, is key for gaining a deeper understanding of these disparities. Many localized factors play a significant role in these ponds, as they are intricate community-managed systems. Groundwater influence, invasive species presence, urbanization, and localized pollution should all be considered in future studies.

4.3 Future Recommendations

Incorporating ground truth observations with remote sensing data is expected to realize important improvements in the understanding of Hawaiian aquaculture systems. Specifically, additional turbidity, salinity and chlorophyll-a values as well as fish recruitment and mortality rates could provide deeper insights into the complex ecological dynamics at play within these environments. Additionally, integrating indigenous knowledge of loko i'a dynamics will enhance the interpretation of satellite data, offering a clearer understanding of these traditional aquaculture systems.

5. Conclusions

This project used NASA Earth observations and remote sensing analysis techniques to create three products that we hope will aid KUA and local practitioners with fishpond restoration efforts for improving the stock of native awa and ‘ama ‘ama fish species. Ocean surface temperatures were shown as a time series over the statewide region and within individual fishponds that showed sheltering between east and west sides of the island. Visual analysis on pond surface temperatures found that small, unsheltered fishponds are more likely to exceed thermal thresholds for juvenile fish. Sheltered ponds, however, appear more capable of handling temperature fluctuations during the dry season without threatening the health of the juvenile fish populations within loko i'a. Pond size also seemed to play a role in determining temperature resilience, but a larger sample of ponds would be necessary to draw concrete conclusions. Within loko i'a there was no clear relationship between NDCI and temperature, warranting further analysis of the mechanisms regulating chlorophyll-a within fishponds. To contribute to our partners outreach initiatives, communication materials were also developed to increase education and awareness of loko i'a conservation, the influence of marine heatwaves, and how NASA Earth observations fit into the domain of Hawai'ian coastal conservation research.

6. Glossary

‘Ama ‘Ama – Striped Mullet (*Mugil cephalus*)
Awa – Milkfish (*Chanos chanos*)
Earth Observations – Satellites and sensors that collect spatial and temporal information about the Earth's physical, chemical, and biological systems
ECOSTRESS – ECOsystem Spaceborne Thermal Radiometer Experiment
GEE – Google Earth Engine, code editor that has open access to NASA Earth observations
ISS – International Space Station
Kuapa – seawater loko i'a
Loko i'a – Reiterate the definition here in the glossary since "Loko i'a" and "Fishponds" are used interchangeably quite often in the paper, which I think should be fine if we list in the glossary so it's easier for the reader.
Loko i'a kalo – freshwater planted with taro loko i'a
Loko pu'uone – brackish water loko i'a
Loko ‘umeiki – fish trap loko i'a
Loko wai – freshwater loko i'a
Marine Heatwave – Period of abnormally high ocean temperatures
MODIS – Moderate Resolution Imaging Spectroradiometer
NDCI – Normalized Difference Chlorophyll Index, measurement of chlorophyll-a content that can indicate the productivity of a waterbody.
OLI – Operational Land Imager
Red Edge – range of rapid change in reflectance of vegetation within electromagnetic spectrum
Revisit Period – How often a satellite passes over the same location and obtains usable imagery. Recorded as days between each image snapshot.
TIRS – Thermal Infrared Sensor

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9. Appendices

Appendix A: 15 mile Coastal Buffer Zone

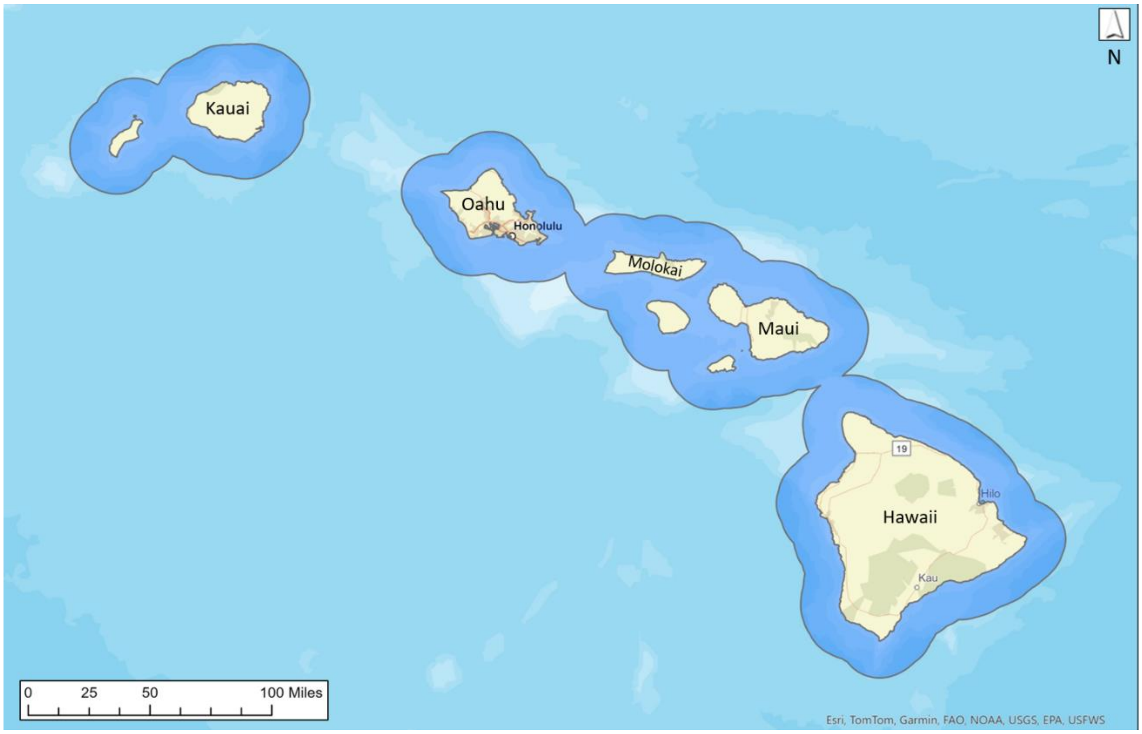

Figure A1. Secondary regional study area used to compare chlorophyll-a and temperature along coastal areas. surrounding Hawaii.

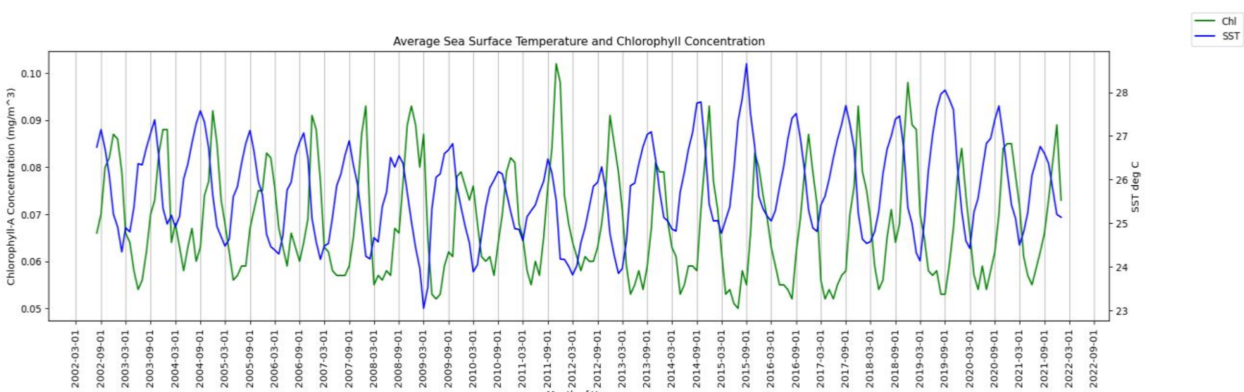

Figure A2. Time series showing average chlorophyll-a concentration (green) and sea surface temperature (blue) from Aqua MODIS between August 2002 to December 2021.

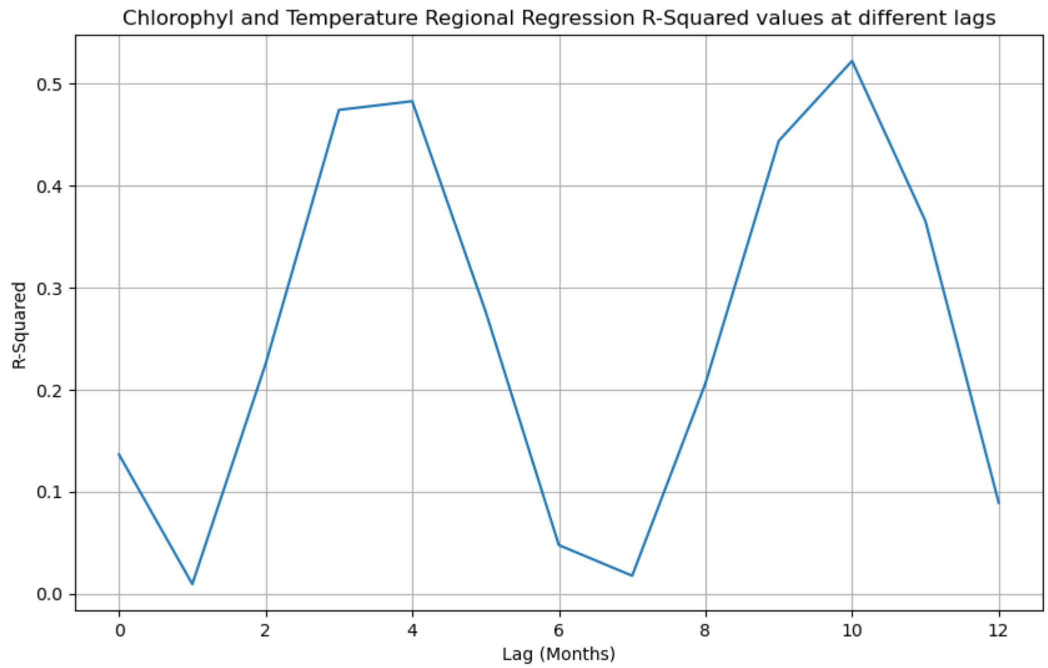

Figure A3. Line plot of R^2 values from several linear regressions correlating temperature and chlorophyll-a in the local oceans of Hawai'i. X-axis indicates the number of months the chlorophyll-a values were offset to show how long after a temperature value occurs we observe an obvious connection to a later chlorophyll-a event.