Event:

In 1902, Red Mangrove (*Rhizophora mangle*) from Florida was introduced to the south shore of Moloka'i (D'Iorio *et al.* 2007) at Pālā'au by the Moloka'i Ranch to prevent soils destabilized by the overgrazing of feral and domesticated ungulates from reaching the adjacent coral reef. In 1993, NASA first confirmed sea level rise (SLR) by satellite observations, and projects SLR will continue to rise this century.

Problem:

Red Mangrove has invaded the area between the shoreline and the fringing reef on Moloka'i, which threatens the long-term sustainability of coastal resources used for subsistence by the island's residents (i.e. octopus, crab, fish, seaweed). These resources are vital to families for economic, cultural, and social reasons. Sea level rise may further impact this area and encroach the terrestrial landmass along the south shore, thereby increasing the current mangrove infestation by inland expansion.

Question:

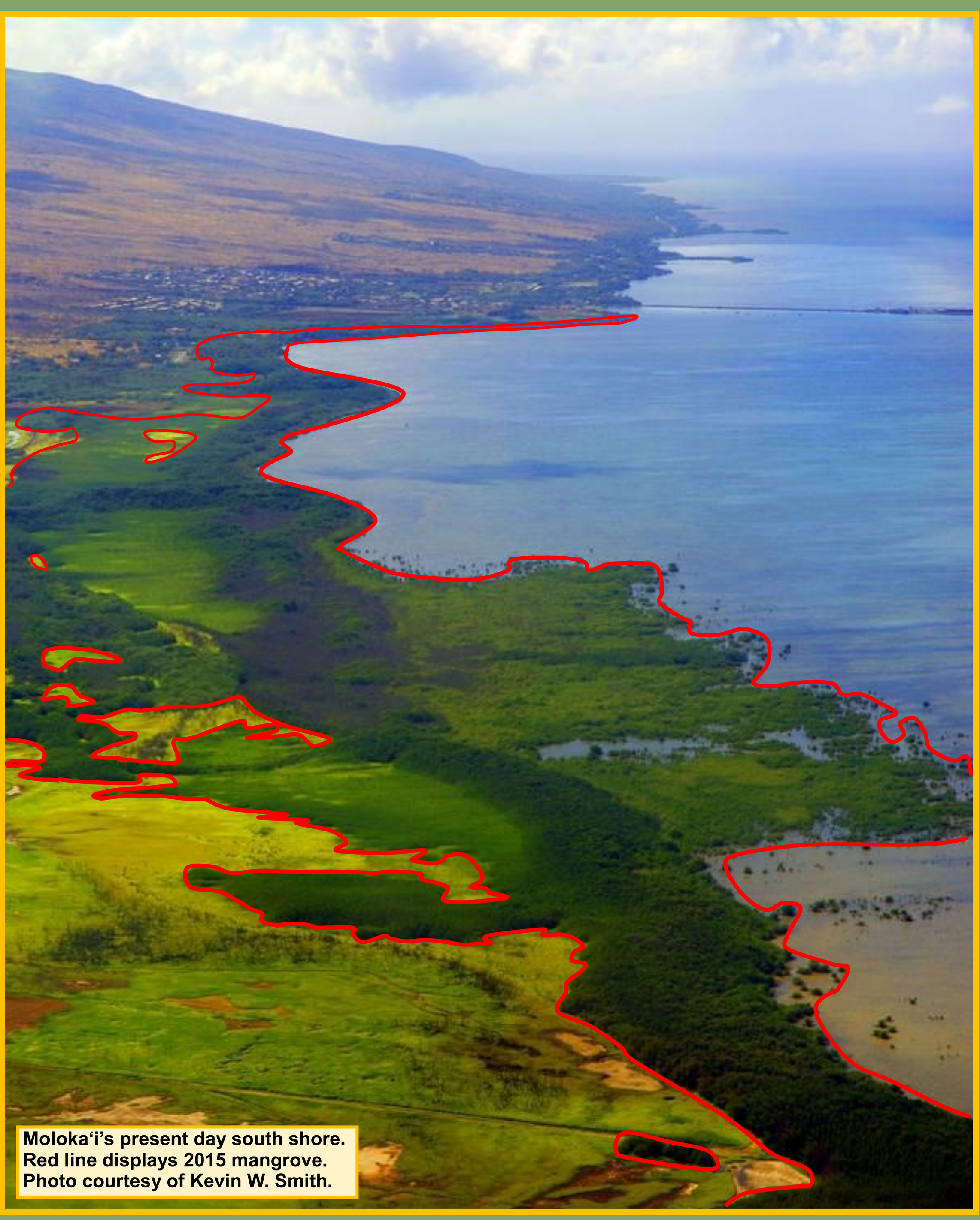
This study explores these questions:

1. Does Red Mangrove have the potential to reach Moloka'i's fringing reef? If so, how long will it take to establish a cultivating population?
2. To what extent will sea level rise affect the mangrove population both seaward and terrestrially?
3. How will sea level rise and mangrove expansion affect Moloka'i residents economically, culturally, and socially?

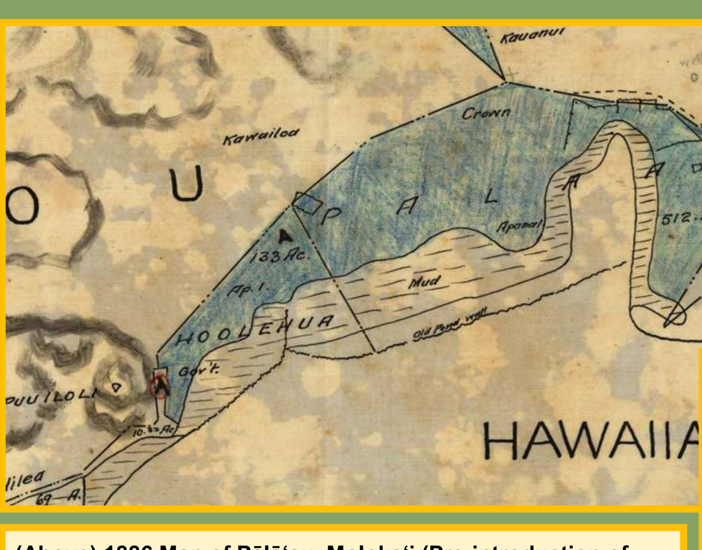
Hypothesis:

1. Geographic Information System (GIS) analysis of aerial imagery and historic maps will identify the seaward and terrestrial progradation rate of Red Mangrove along the south shore of Moloka'i with the incorporation of sea level rise.
2. Benthic and terrestrial modeling will determine the eventual full extent of mangrove on Moloka'i.
3. Residential, recreational, visitor, business/property owner, and cultural practitioner/subsistence surveys will identify the socioeconomic impacts of mangrove's invasion and place a monetary value on the island's fringing reef. Survey results will determine the cost to benefit transfer between removal costs and economic value of the southern coast.

(Above) Photos A. M. Alexander, courtesy of the Museum of Vertebrate Zoology, Berkeley, CA.
Left: Moloka'i's south shore looking south. Right: Moloka'i's south shore looking eastward.

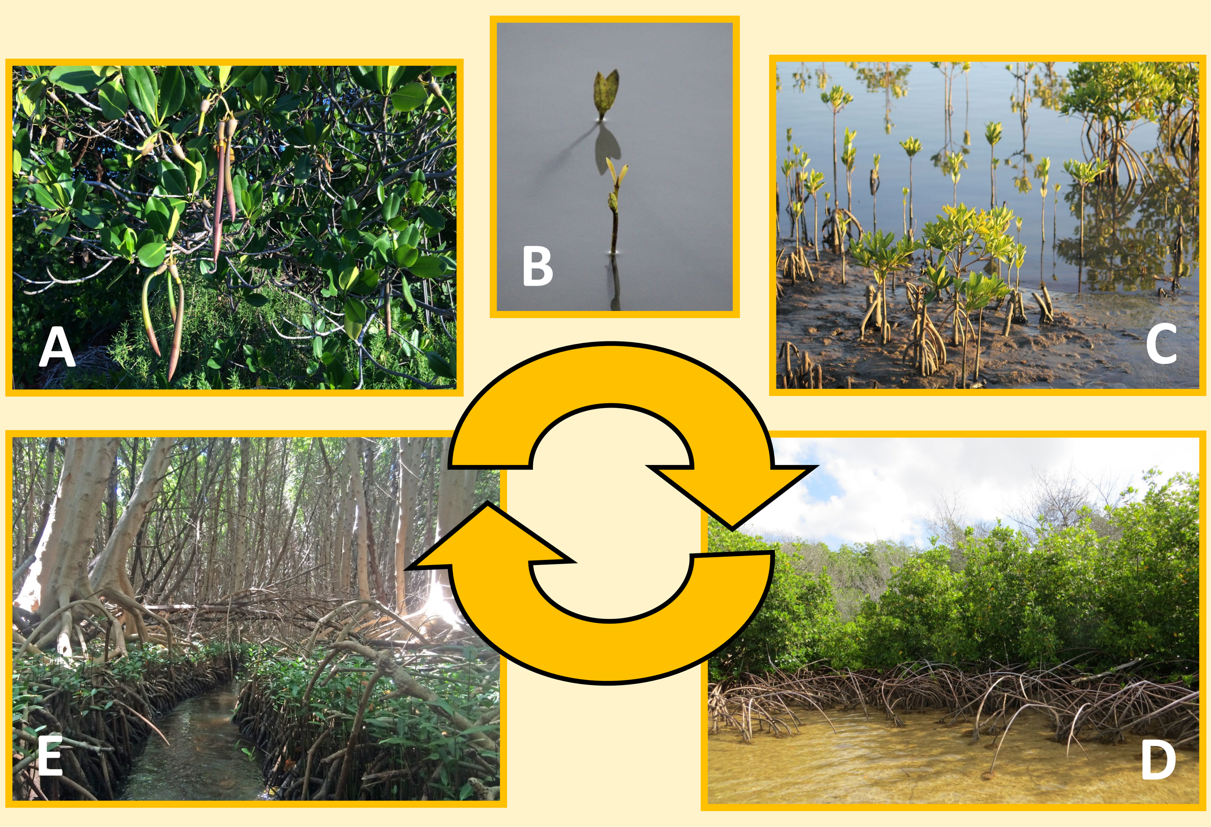


Moloka'i's present day south shore.
Red line displays 2015 mangrove.
Photo courtesy of Kevin W. Smith.



(Above) 1886 Map of Pālā'au, Moloka'i (Pre-introduction of mangrove). Map by M.D. Monsarrat.

(Right) 1915 Map of Pālā'au, Moloka'i (Post-introduction of mangrove). Map by U.S. Coastal Geodetic Survey.



Mangrove maturation cycle:

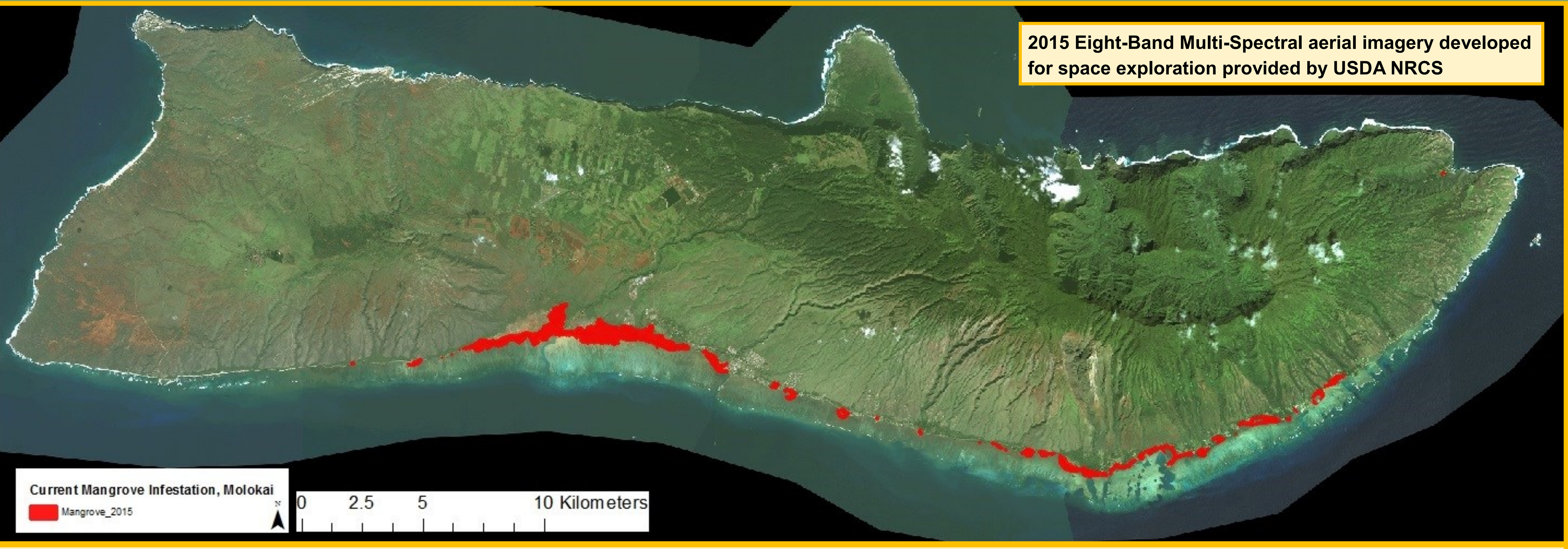
A. Propagules hanging from mature trees grow in dense, low-hanging clusters. These pencil-shaped fruits contain embryonic root structures that germinate while still on the tree and are dispersed by wind, currents, and tide.

B. Young mangrove seedlings at various stages of root development find a host in mudflats, plant their roots, grow leaves, and flower.

C. Mangrove seedlings take root. Roots contain pores called lenticels that promote respiration in anaerobic soil (low-oxygen) by diffusing oxygen from top soil down to the buried roots when exposed at low tide, and excludes salt while extracting fresh water from soils (non-metabolic ultrafiltration system).

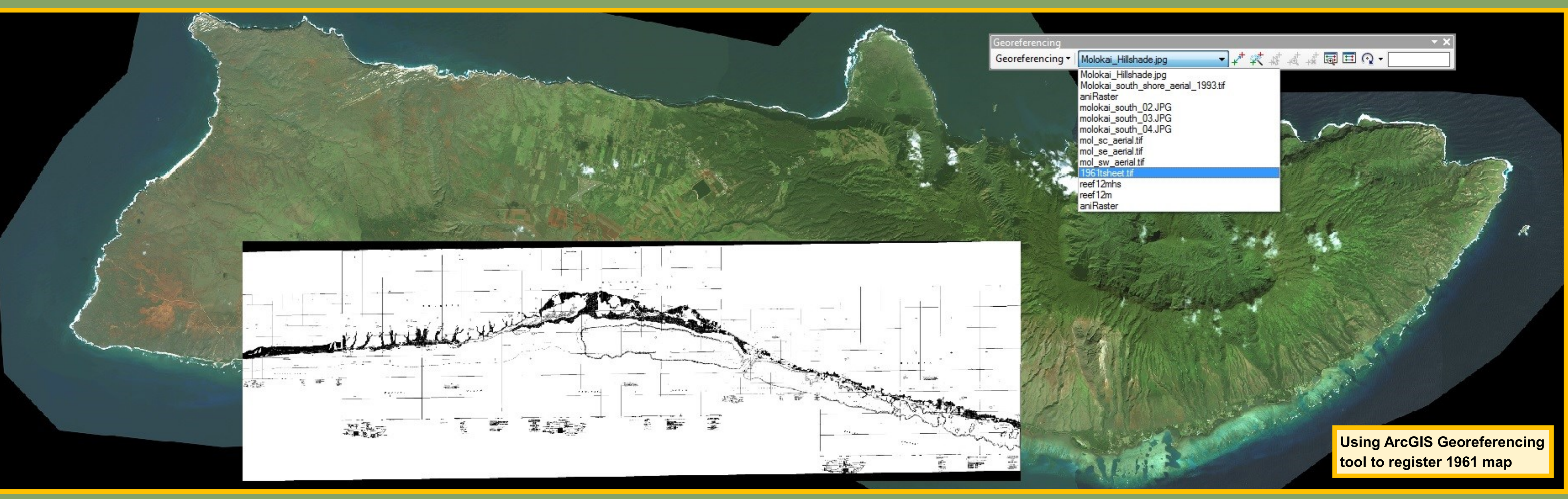
D. Mangrove tree establishing a stronghold. Aerial prop root system extends over one meter above surface soil providing adaptability to intertidal habitat. Maximum water depth for survival: 0.5 meters below lowest low tide mark.

E. Mangrove forest dense root systems trap sediments and uptake nutrients from water and soil.

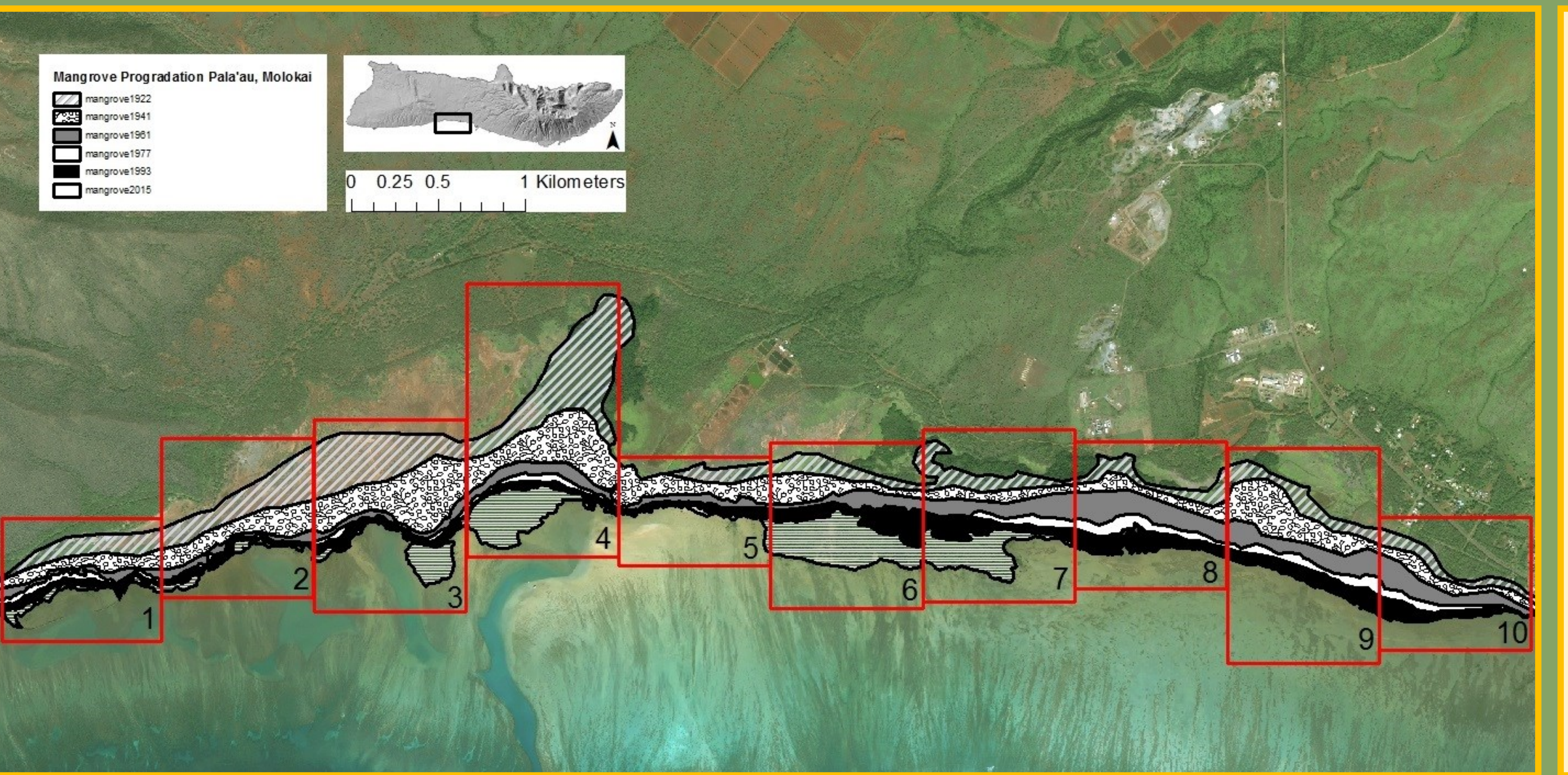


2015 Eight-Band Multi-Spectral aerial imagery developed for space exploration provided by USDA NRCS

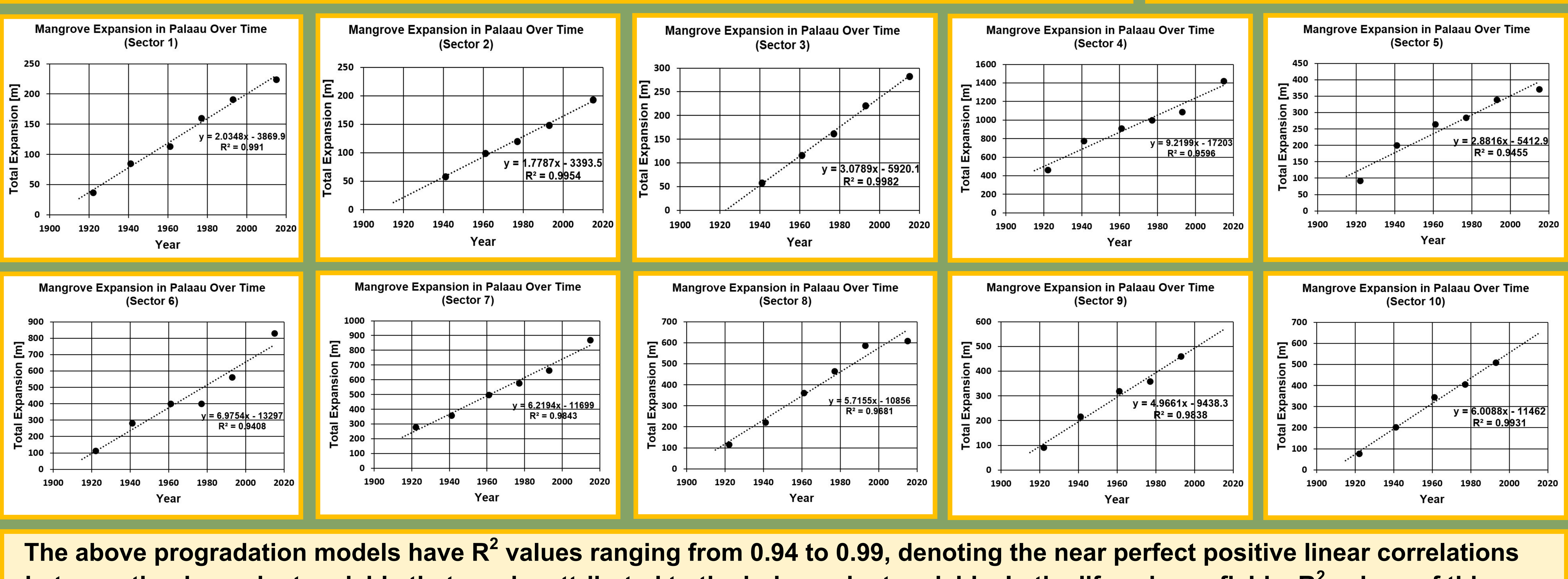
Red Mangrove is a salt tolerant, woody plant native to Florida that is characteristically found in intertidal and coastal zones. Due to its physiological and morphological adaptations, the species is able to thrive in Hawai'i's unique environment and harsh conditions such as high wave action and tidal inundation, high salinity, and anaerobic substrates.



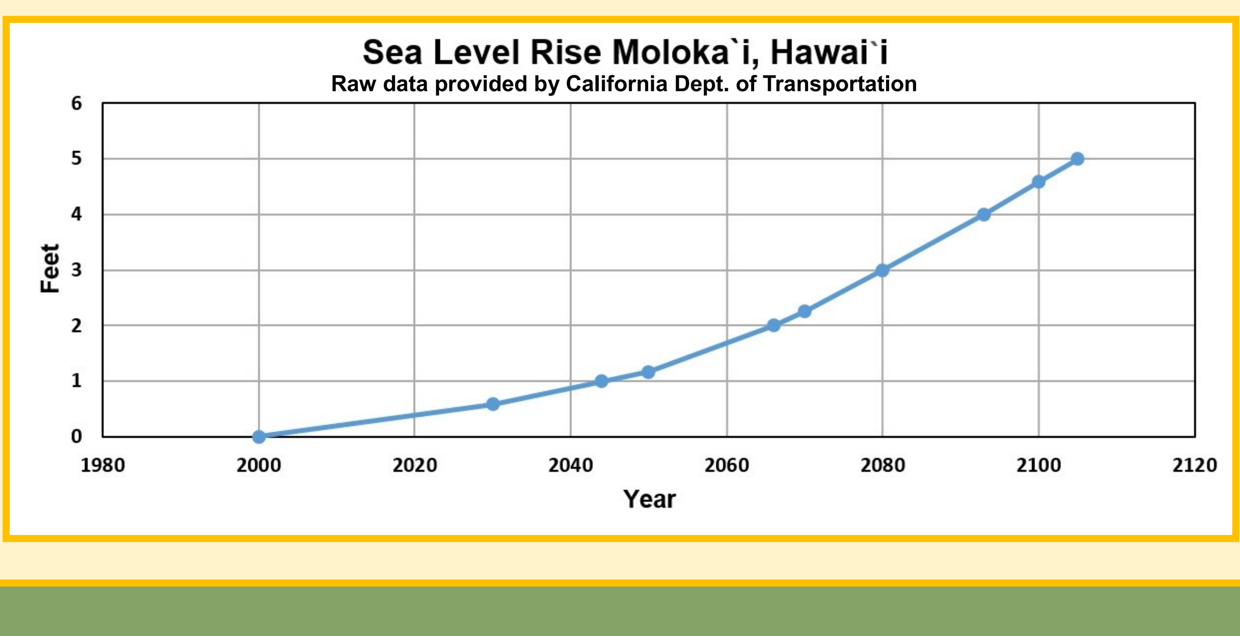
Using ArcGIS Georeferencing tool to register 1961 map



Mapping (left) displays the increasing total area of Red Mangrove expansion over time from 1915, 1922, 1941, 1961, 1977, 1993, 2000, 2013, 2015. Red Mangrove has expanded Moloka'i's shoreline linearly over 1.6 kilometers in the past century. Mangrove is currently on track to reaching Moloka'i's fringing reef — the longest in the United States — within the next 75 years. Based on benthic modeling, Red Mangrove has the potential to establish itself on 66% of the fringing reef.



The above progradation models have R^2 values ranging from 0.94 to 0.99, denoting the near perfect positive linear correlations between the dependent variable that can be attributed to the independent variable. In the life science fields, R^2 values of this significance substantiate the prediction that Red Mangrove will reach Moloka'i's fringing reef within the next 75 years. (http://condor.depaul.edu/sjost/it223/documents/correlation.htm)



Background of Sea Level Rise:

Over the past 100 years, human activities and use of fossil fuels has resulted in greenhouse gases permeating the atmosphere. These emissions allow sunlight to heat the earth's surface causing a rise in temperature. This has become known as climate change. Oceans absorb about 80 percent of this heat which expands the oceans causing sea level rise (NOAA) (https://www.ncdc.noaa.gov/monitoring-references/faq/greenhouse-gases.php).

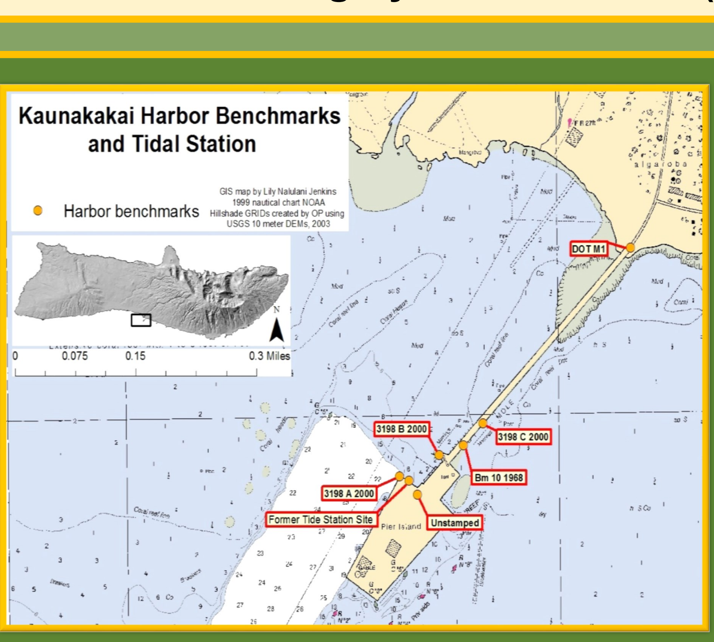
SEA LEVEL RISE and MARCH OF THE MOLOKA‘I MANGROVE

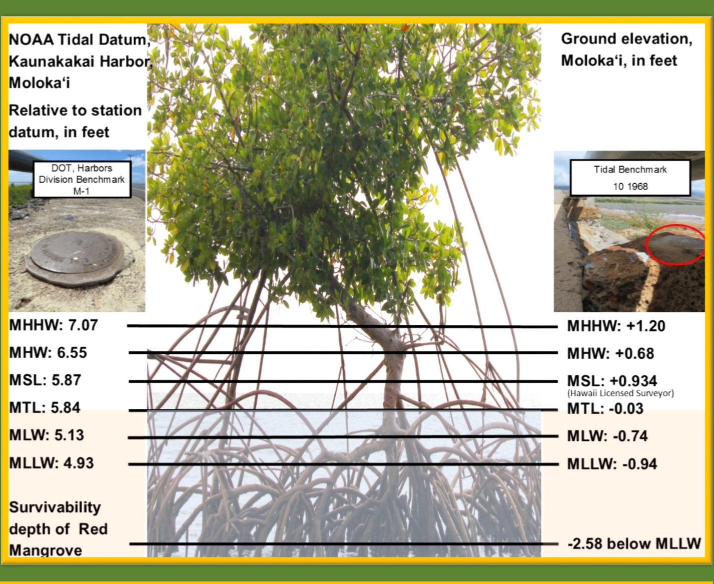
The Socioeconomic and Environmental Impacts of Sea Level Rise and Introduced Red Mangrove (*Rhizophora mangle*) on Moloka‘i, Hawaiian Islands

Above image is the 2006 FEMA dataset containing NoData cells shown within the gray-scale as white (rooftops) or color (vegetation).

Methodology:

Thematic maps classify baseline resources and are an essential tool to evaluate change and identify threats in a coastal ecosystem. Geographic Information System (GIS) software was used to interpret satellite data, aerial imagery, historic maps and coastal charts, to identify the position of Moloka‘i’s south shoreline, map sea level rise (SLR) and the seaward migration of Red Mangrove, analyze the ecological effects of each, and predict their future impacts on the reef flat. The 2006 Federal Emergency Management Agency (FEMA) LiDAR dataset was acquired to obtain digital elevation models (DEM) of Moloka‘i’s south shore. The FEMA dataset contained “NoData” cells and required the geospatial analysis tool “Natural Neighbor” to calculate and fill missing elevations. The projections in this model are based on mean sea level using U.S. Standard Units as this is how the FEMA dataset and tidal datum was developed.





The calculation of sea level rise (SLR) required conversion of local tidal datum (water levels) to land elevation as this model is based on terrestrial inundation. This required the tidal benchmark disks for Moloka‘i be located at Kaunakakai Harbor and the associated tidal datum be obtained from the National Oceanic Atmospheric Administration (NOAA) and converted to a land elevation utilizing Hawai‘i Dept. of Transportation, Harbors Division benchmark M-1, with GPS elevation data for this benchmark provided by a Hawai‘i Licensed Surveyor.

The projected rise of 1 foot will transfer the shoreline terrestrially approximately 84 meters from its current position and inundate 2,812,101 m^2 of land (Figure 1). The projected rise of 2 feet will transfer the shoreline terrestrially approximately 564 meters from its current position and inundate 19,515,477 m^2 of land (Figure 2). The projected rise of 3 feet will transfer the shoreline approximately 782 meters from its current position and inundate 45,021,920 m^2 of land (Figure 3). The projected rise of 4 feet will transfer the shoreline terrestrially approximately 956 meters from its current position and inundate 58,484,769 m^2 of land (Figure 4). The projected rise of 5 feet will transfer the shoreline terrestrially approximately 1,023 meters from its current position and inundate 67,985,172 m^2 of land (Figure 5).

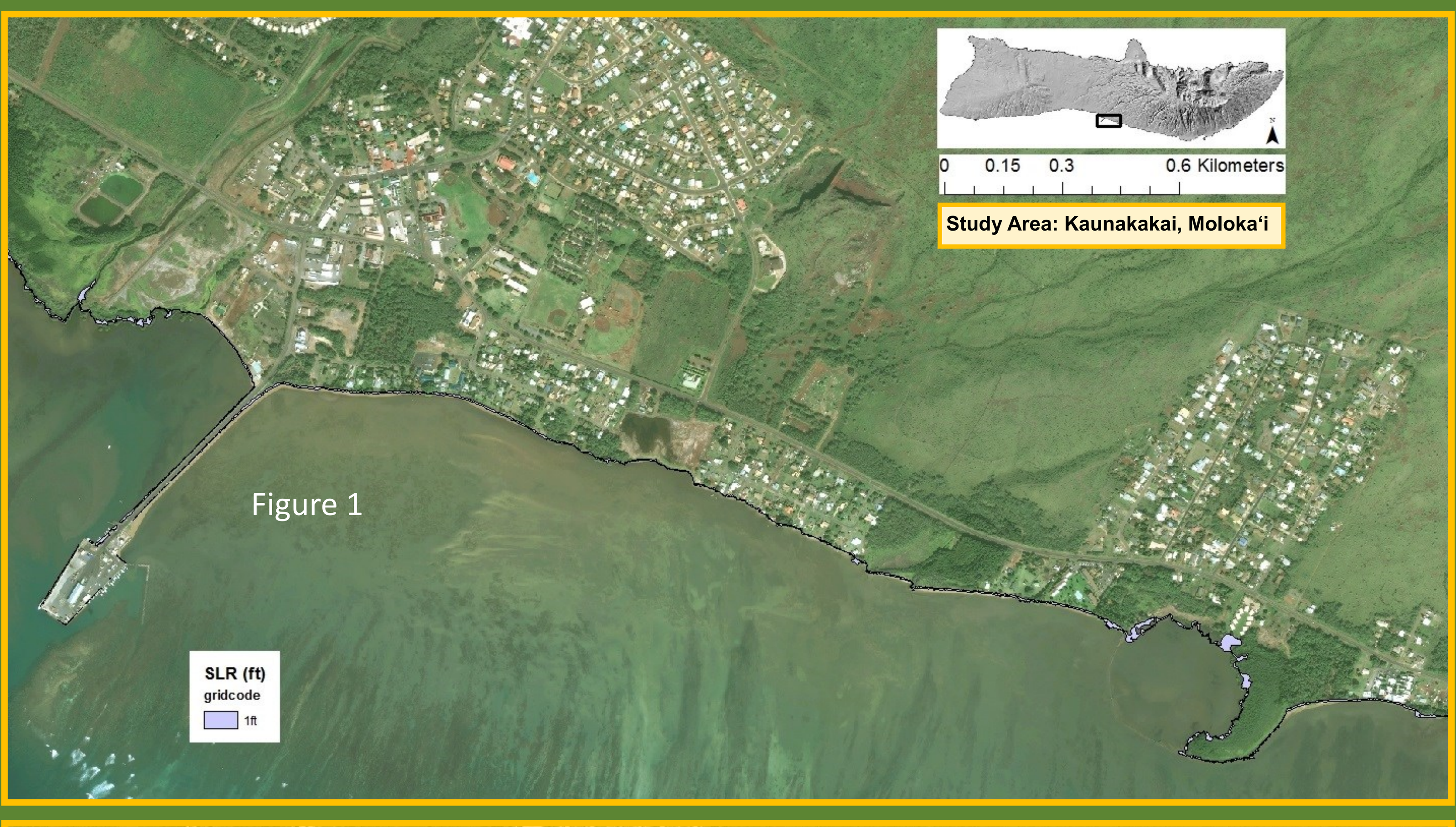


Figure 1

Figure 2

Figure 3

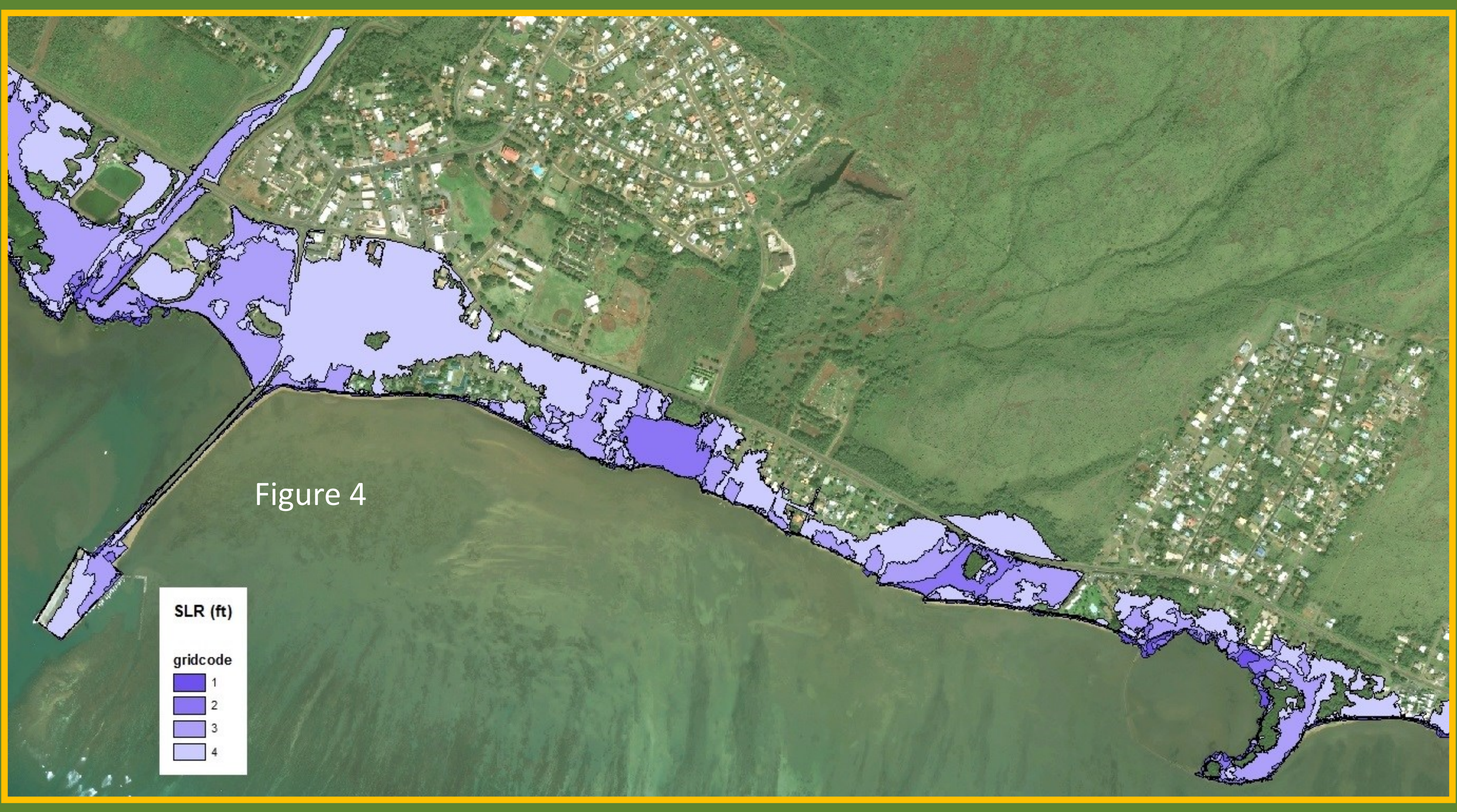


Figure 4

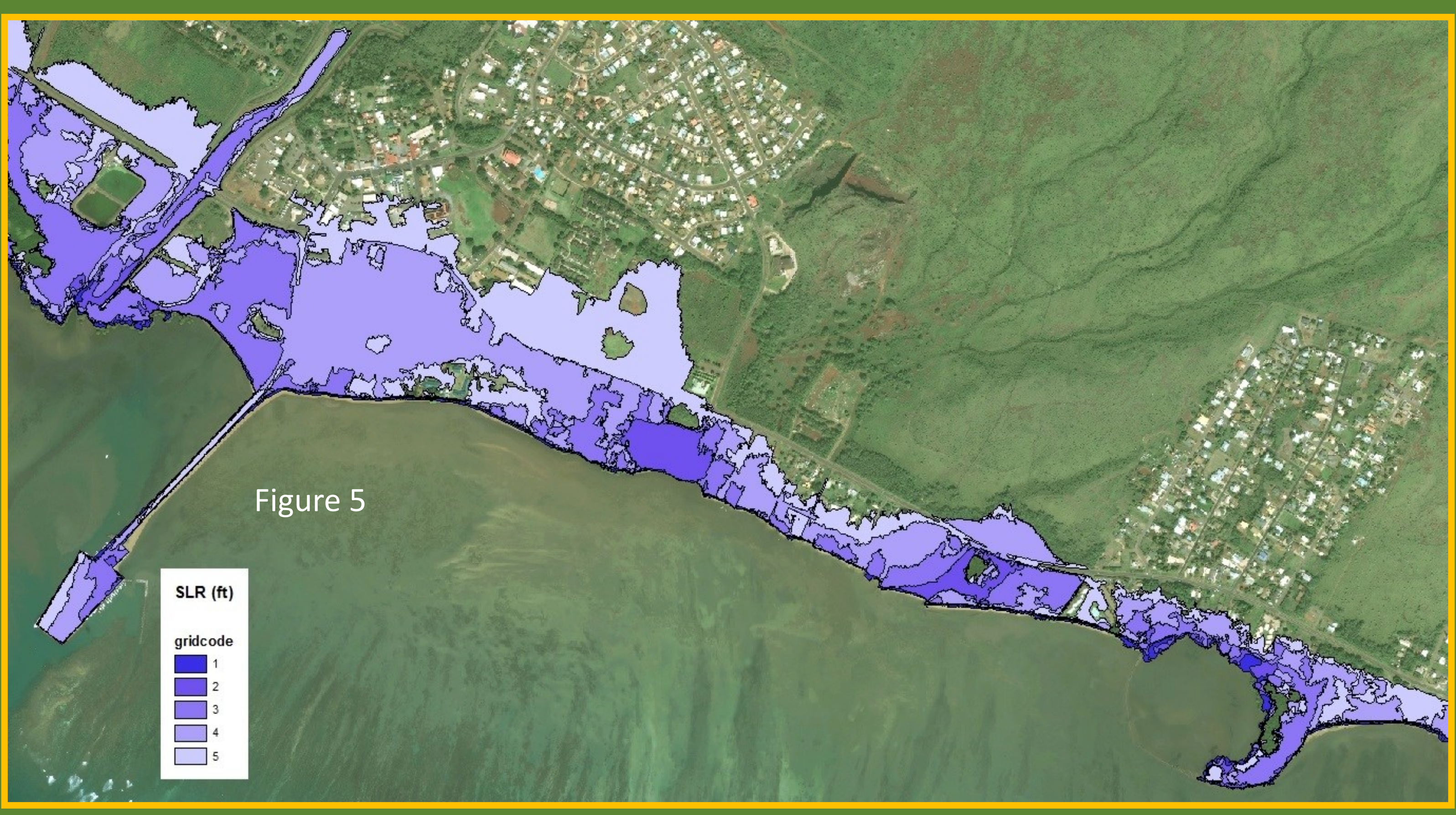
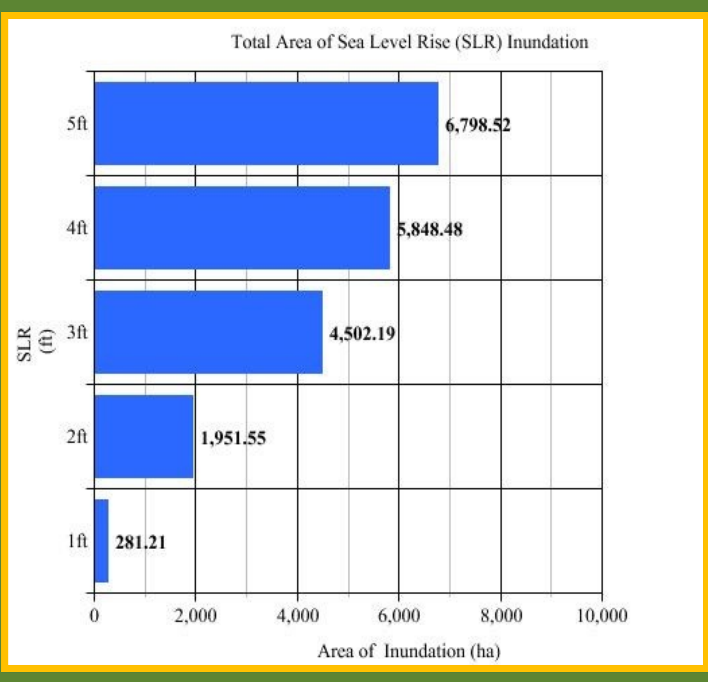
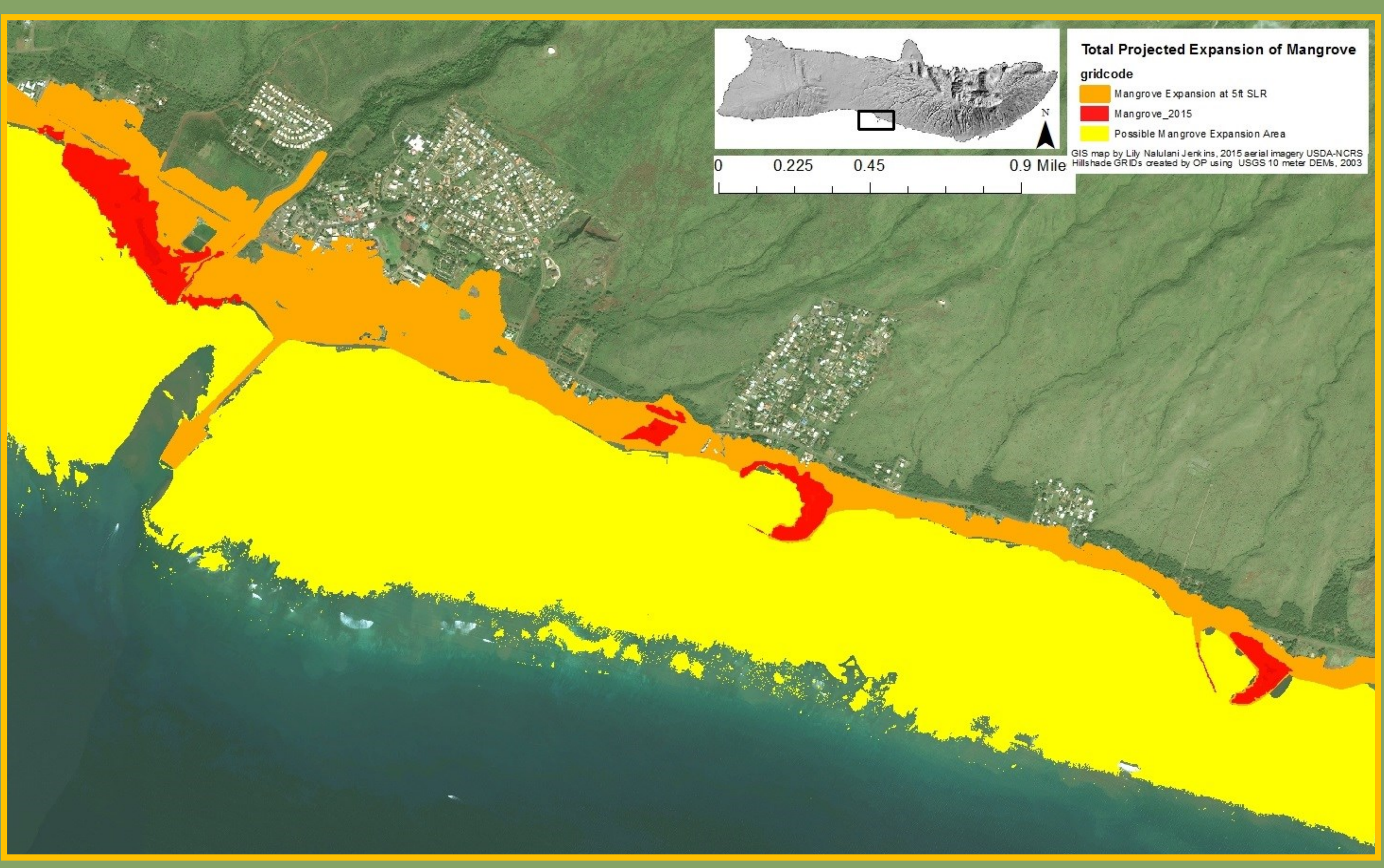


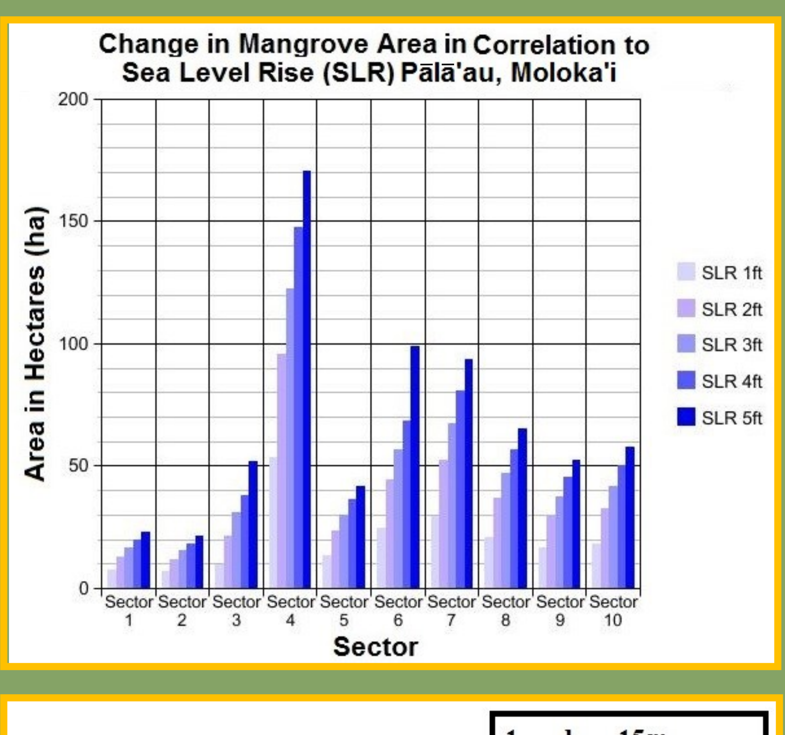
Figure 5



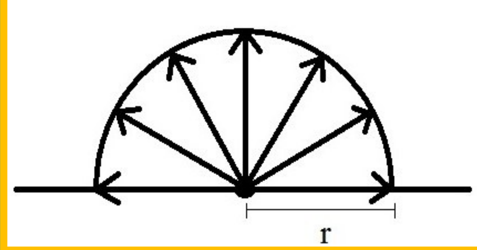
Year	Inches	Feet
2000	0	0
2030	7	0.58333
2044	12	1
2050	14	1.16667
2066	24	2
2070	27	2.25
2080	36	3
2093	48	4
2100	55	4.58333
2105	60	5



The image above displays the maximum extent of Red Mangrove infestation along Moloka‘i’s south shore. Orange represents mangrove infestation with sea level rise, red displays the current established mangrove, and yellow represents a benthic model which was programed to only calculate and map areas along the south shore of Moloka‘i that reach a depth of 0.5 meters below the low tide mark.



Equation for Circular Progradation



1. $\frac{dr}{dt} = \frac{15m}{1yr}$
2. $r = 15 * (x\ years)$
3. $Area = \frac{1}{2}\pi r^2$
4. $\frac{dA}{dt} = \frac{1}{2}\pi(2r)\frac{dr}{dt}$
5. $\frac{dA}{dt} = \frac{1}{2}\pi(2r)15$
6. $\frac{dA}{dt} = \pi r 15$

All photos, graphs, tables, and images created by Lily N. Jenkins unless credited otherwise.

Total Economic Value (TEV) of Moloka‘i’s Fringing Reef

Use and non-use values of coral reefs have associated net economic benefits (Spurgeon 1992). “The value of the sum of compatible uses of these goods and services form the total economic value of coral reef ecosystems.” (Cesar and van Beukering 2004)

Use Values

Use values are net benefits from the actual use of the fringing reef ecosystem.

- ⇒ Subsistence
- ⇒ Tourism
- ⇒ Recreation
- ⇒ Property Value
- ⇒ Research
- ⇒ Business Value

Non-Use Values

Non-use values include an existence value which reflects the value of an ecosystem to humans whether it is used or not.

- ⇒ Endangered Species
- ⇒ Archeological Sites
- ⇒ Invasive Species
- ⇒ Cultural

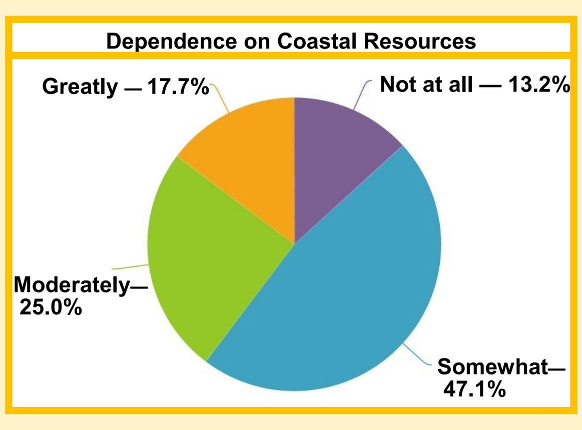
Subsistence

Moloka‘i’s fringing coral reef is essential for the livelihood of 38% (Matsuoka, McGregor and Minerbi 1994) of the island’s residents which practice subsistence gathering (chiefly fishing) to reduce their food expenditures. Historically fishponds and fishtraps guaranteed a food supply for the population, but with destruction of these by mangrove and the increased costs of living, many residents have returned to fishing and gathering to supplement food for their family. Other aquaculture on Moloka‘i includes commercial shrimp farms contributing to the economic base of the island.

Residential Use of Coastal Areas

Pole or line fishing	87.0%
Gill-netting	30.0%
Throw-netting	40.0%
Spearfishing	65.0%
Torching	25.0%
Seafood-trapping	15.0%
Trolling/bottom fishing	35.0%
Surround-netting	20.0%

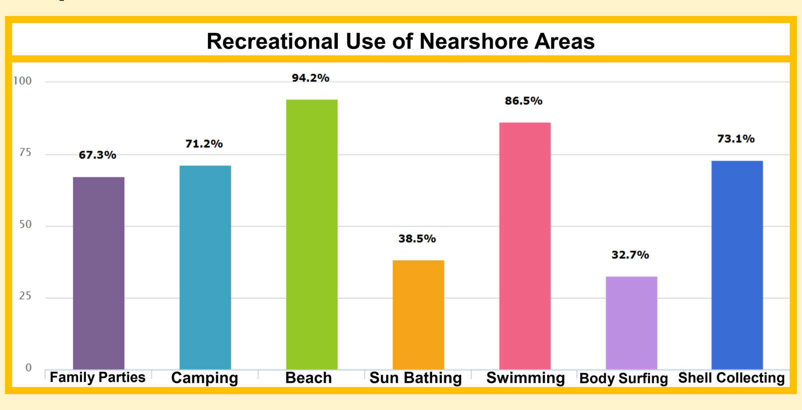
Dependence on Coastal Resources



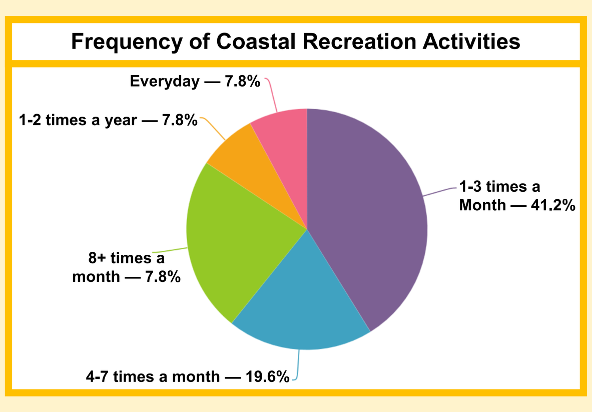
Recreation

Coastal ecosystems play an important role in recreational activities along the south shore of Moloka‘i. Both producers and consumers benefit from practices such as camping, shell collecting, sun bathing, swimming, body-surfing, snorkeling, etc. The recreational value of coral reefs on Moloka‘i is approximated by the sum of the consumer and the producer surplus.

Recreational Use of Nearshore Areas



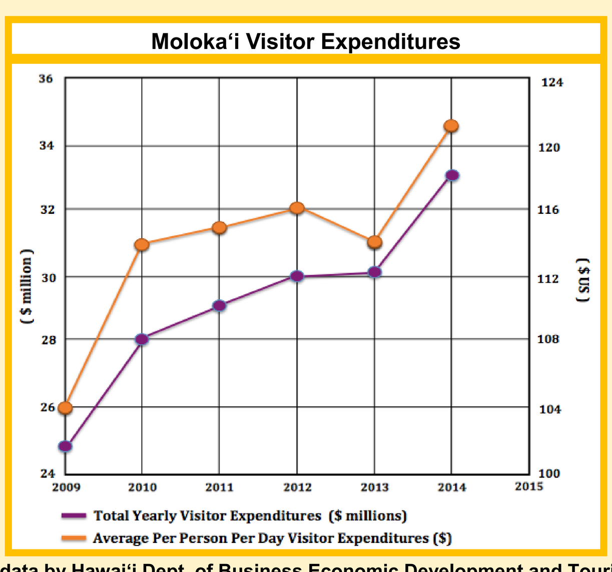
Frequency of Coastal Recreation Activities



Tourism

Every year, tens of thousands of tourists visit beaches and coastal areas protected by Moloka‘i’s fringing reef. The local economy receives millions of dollars from these visitors through diving tours, recreational fishing trips, hotels, restaurants, and other businesses, which all contribute to Moloka‘i’s economic direct use values.

Moloka‘i Visitor Expenditures



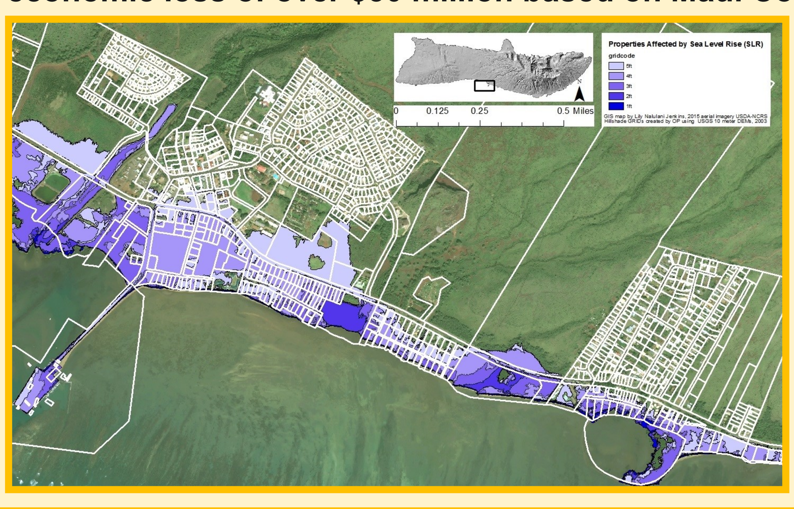
Raw data by Hawai‘i Dept. of Business Economic Development and Tourism

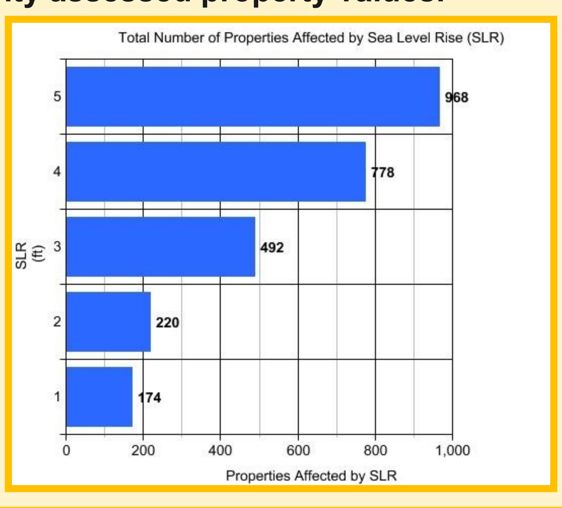
Moloka‘i Visitor Coastal Activities

Family Parties	16.7%
Camping	9.3%
Beach	68.5%
Sun Bathing	13.0%
Swimming	48.2%
Shell Collecting	24.1%
Surfing/ Body-bording	16.7%
Stand Up Paddling	13.0%
Canoe Paddling	7.4%
Snorkeling	29.6%
Sailing	1.9%
Small-craft Boating	9.3%
Wind Surfing	0.0%
Diving/ Fishing	13.0%

Property Value

Mangrove has established itself on over one hundred south shore properties. Of these properties, mangrove affects 25% of the combined property area, amounting to a total 1,798,649 m^2. Sea Level rise will impact about 1,000 south shore properties resulting in economic loss of over $30 million based on Maui County assessed property values.



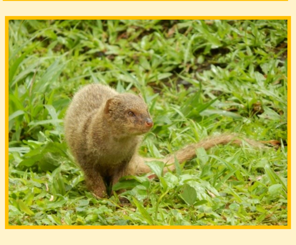


Endangered Species

Mangrove has contributed to the loss of habitat for migratory shorebirds and four endemic waterbirds, including the Hawaiian Coot (left), and the Bristle-thighed Curlew (right), the Official Bird of Moloka‘i.

Invasive Species

Mangrove has become a host to many invasive species including Barn Owl (top right), mongoose (bottom right), Cattle Egret, rodents, and aquatic life forms that further change coastal ecology and support the predation of native flora and fauna. Photos: Forest Starr & Kim Starr



Archaeological and Cultural Sites

Red Mangrove damages sensitive archeological sites with the premature infilling of historic fishponds and fishtraps and destruction of their foundational rock walls. Mangrove is restructuring Moloka‘i’s native coastal ecosystems through its sediment deposition (composting leaf litter and peat), resulting in seaward progradation of the shoreline and conversion of ocean into dry land and loss of the reef flat.

Ancient Hawaiian fishponds on Moloka‘i’s coastline

Invasive Red Mangrove has spread along Moloka‘i’s south shore and is now colonizing six of the eight main Hawaiian islands. Sea level rise will inundate over 16,000 hectares of land on Moloka‘i, and when combined with the projected mangrove infestation, much of the cultural nearshore artifacts on the island, connections to traditional collection sites and subsistence practices will be lost forever.

Benefit Transfer

Data collection surveys were carried out to determine a TEV of Moloka‘i’s fringing reef adapting techniques from the study Economic Valuation of the Coral Reefs of Hawai‘i Final Report (Cesar *et al.* 2002): Analysis utilized the TEV formula from Cesar and van Beukering (2004). The practice of transferring of monetary values is termed ‘benefit transfer’, and many of the attributes taken under consideration in the Cesar and van Beukering study directly relate to the total economic value of Moloka‘i’s fringing reef as both their studies and this study share similar benefit transfers. The total economic value of Moloka‘i’s coral reef as determined by surveys of residents, property owners, and visitors is $150 million per year. The longest fringing reef in the United States is found on Moloka‘i’s southern coastline, and is not only significant for this fact, but for the long-term sustainability of subsistence practices by the island’s residents.

Moloka‘i Mangrove Management and Removal Plan

The GIS mapping in this study detected that 60% of Red Mangrove has infested waters of the state and 40% is found on private properties. This presents a complicated management situation should all mangrove be removed from waters of the state, in that 1) removal on private property is critical to stop production of propagules which can spread to areas where mangrove has been eliminated, and 2) complete eradication and long-term management is impossible without the cooperation of property owners. Legislation that addresses mangrove on private property could potentially undertake this conflict, but not without controversy.

Eradication and Long-term Management Permits Required

Federal

- Historic Site Review - Sec. 106
- USFWS Review - Sec. 6
- Coastal Zone Management Consistency Statement (CZM)

State

- Dept. of Health - 401
- National Pollutant Discharge Elimination System Permit (NPDES)
- Conservation District Use Permit (CDUP)
- Dept. of Land and Natural Resources (DLNR)
- State Historic Preservation Div. Review
- Well Permit (fire protection)

County

- Special Management Area (SMA)
- Grading, Grubbing, and Stockpiling Permit
- Shoreline Setback Variance (and survey)
- Burn Permit

Experimental Mangrove Removal Project to develop removal and/or kill techniques and identify removal costs.

Removal Methodology

- Hand-removal (roots to be cut above ground)
- Propane torch (burn small plants)
- Chainsaws (terrestrial, underwater)
- Herbicide (product for use in saltwater conditions)

Removal Documentation

- Public awareness campaign
- Website to report new infestations
- Events for hand-removal of pods

By-products of Eradication and Long-term Management: Employment

Product Production

- Composting facility
- Lumber
- Charcoal & Biochar
- Tannin dye manufacturing

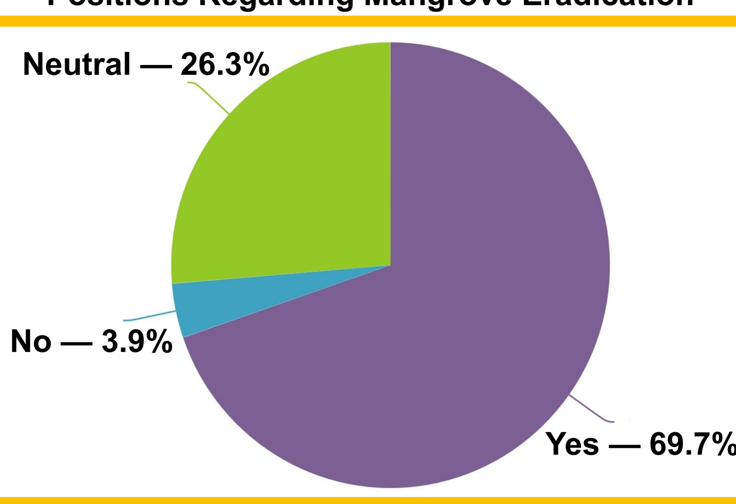
Heavy Equipment Operators

- Excavator
- Trucking & transportation
- Front-end Loader & Backhoe

Office Personnel

- Project supervisors
- Bookkeeper
- Product Sales

Positions Regarding Mangrove Eradication



Potential Areas for Mangrove Management

	Never	Yearly	Monthly	Weekly	Daily
Visitation	15.7%	17.6%	27.5%	27.5%	13.7%
Established in areas use for fish, crab, hunt, etc.	26.0%	18.0%	36.0%	10.0%	10.0%
Fishing in mangroves	54.9%	21.6%	21.6%	0.0%	2.0%
Managing mangrove in fishponds	66.7%	23.5%	5.9%	0.0%	3.9%
Managing shoreline mangroves	52.0%	28.0%	14.0%	2.0%	4.0%
Visiting wetlands	34.0%	36.0%	20.0%	4.0%	6.0%
Visiting beaches	10.0%	14.0%	40.0%	28.0%	8.0%
Mangrove present on private property	93.9%	0.0%	4.1%	0.0%	2.0%
Accessing nearshore waters	15.7%	9.8%	47.1%	17.6%	9.8%

Percentage of Contribution for Mangrove Removal

Value	Percent
Community work day	77.0%
Independently remove	41.9%
Donate money	36.5%
Nothing	5.4%

Conclusion:

Red Mangrove is continuing its march to Moloka‘i’s fringing coral reef, the longest fringing reef in the United States. Within the next 75 years, GIS mapping indicates that Red Mangrove will most likely establish itself upon the fringing reef, regardless of the projection of sea level rise, due to its ability to survive at depths exceeding present conditions and its rapid progradation rate. If Red Mangrove is not managed or eradicated it will result in economic loss exceeding $150 million annually as determined by surveys of residents, property owners, and visitors. Maximum sea level rise on Moloka‘i will inundate 16916 ha^2 of land along the south shore with an economic loss of over $30 million.

Red Mangrove on historic fishpond wall on Moloka‘i’s south shore looking east.