The role of refugia in the persistence and recovery of northern California bull kelp forests

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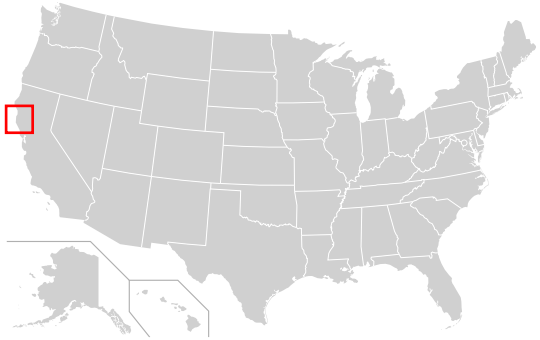
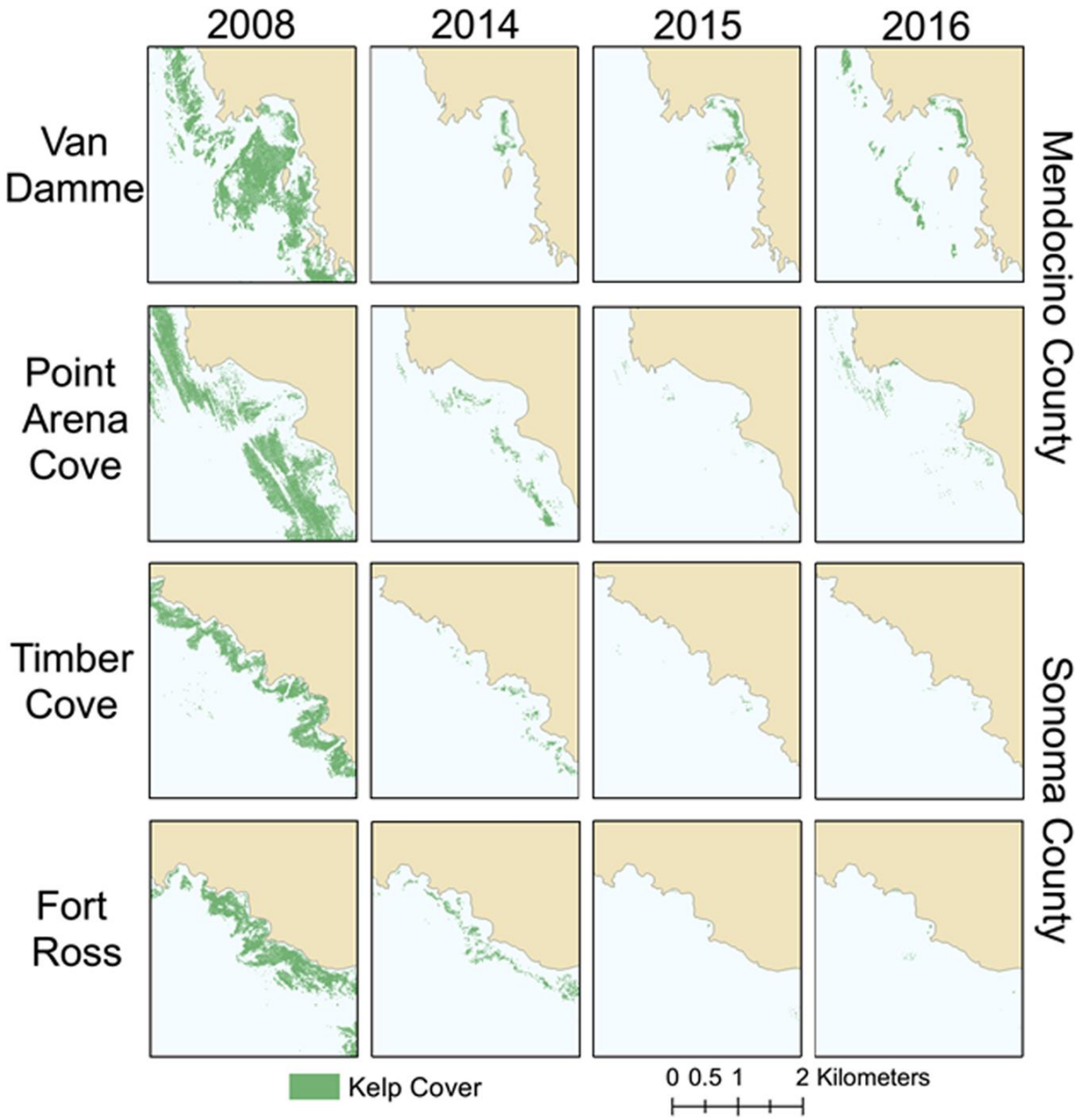
Multiple stressors lead to kelp declines

- Widespread kelp declines (90-95%)
- Small populations visible in 2016 toward the end of the heatwave
- California Department of Fish and Wildlife aerial surveys of surface canopy kelp in Mendocino and Sonoma counties
  - 2 m pixel sizes
  - Last survey completed: 2016





Rogers-Bennet & Catton, 2019

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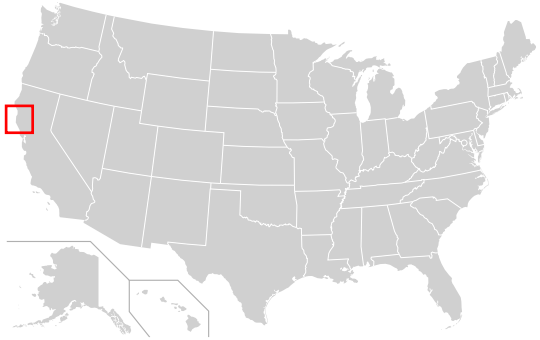

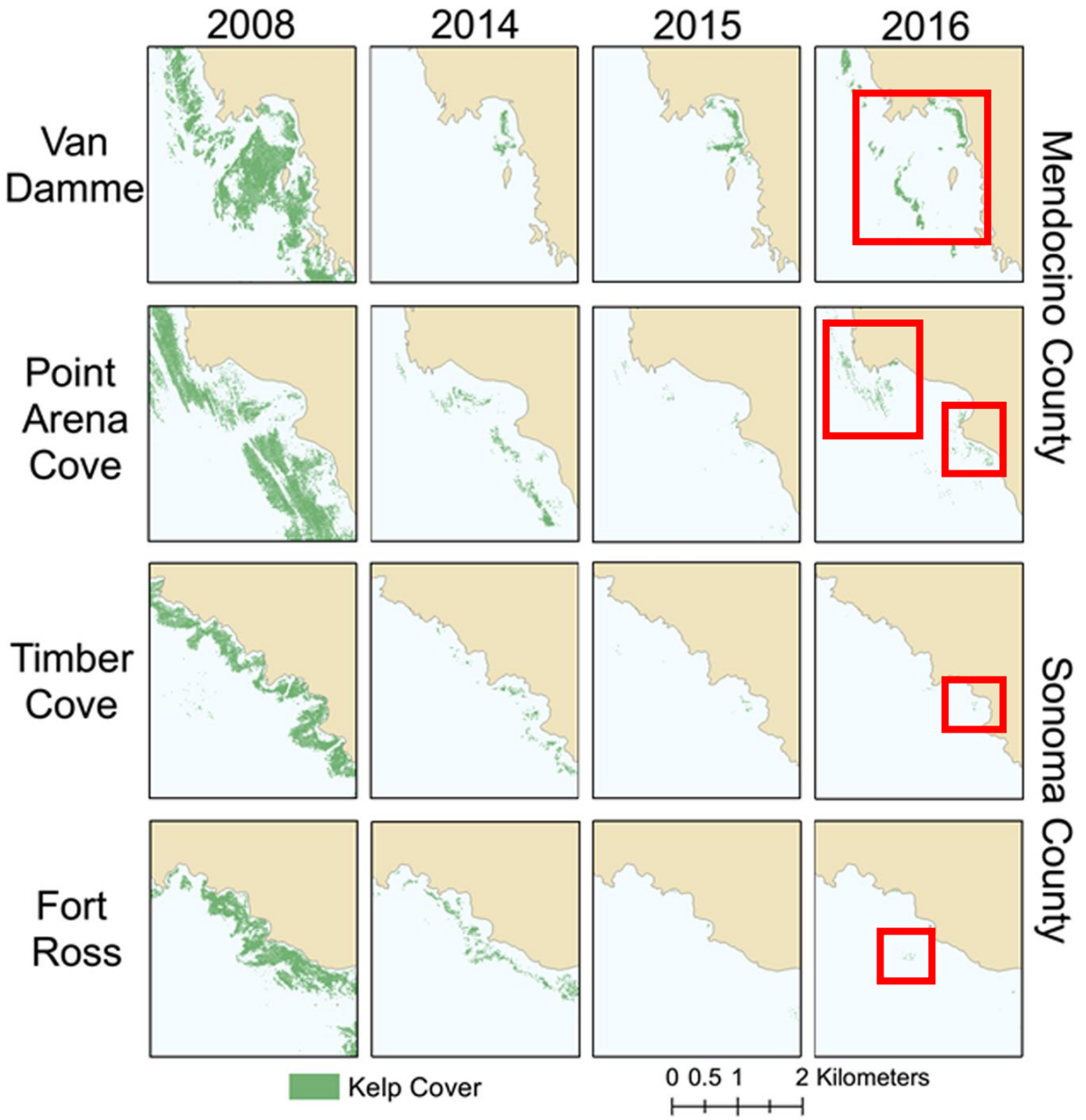

Rogers-Bennet & Catton, 2019

Objectives

1. Fill in missing data from 2017-2022 at a high spatial resolution.

2. Where was bull kelp able to persist?

3. What factors were associated with their persistence?
    1. Temperature
    2. Grazing
    3. Connectivity

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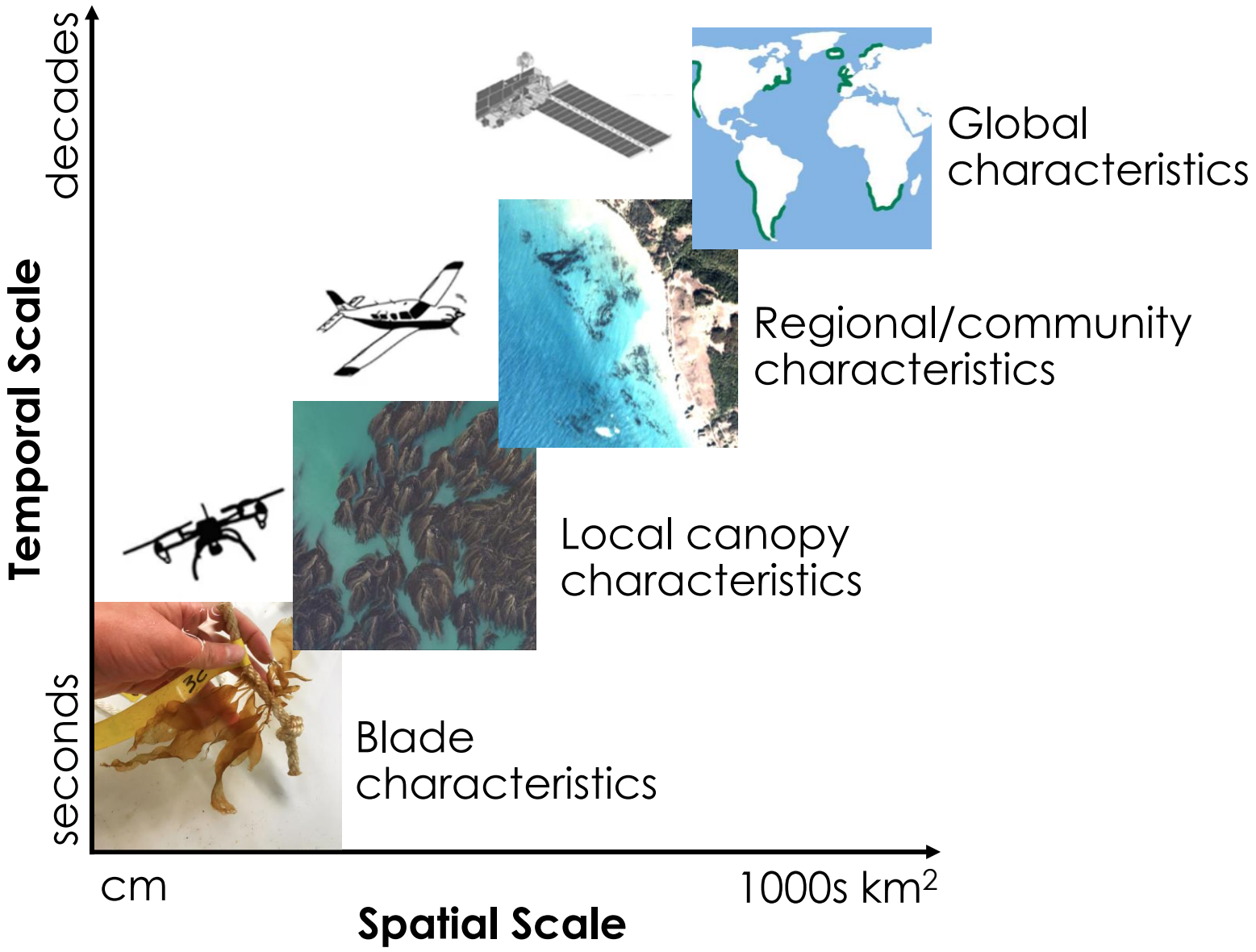
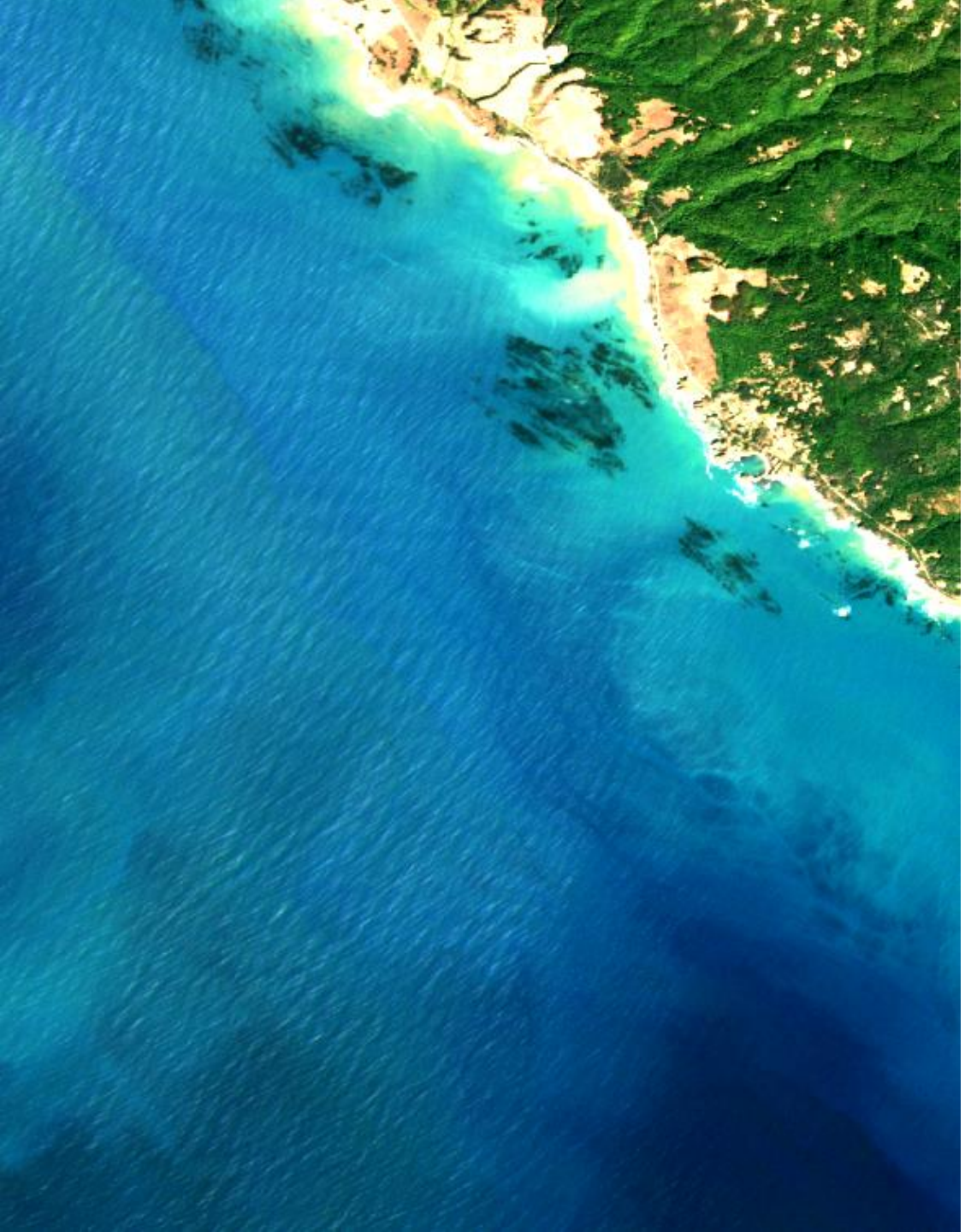
Remote sensing provides the data we need to gap fill other sources



- Remote sensing is becoming increasingly utilized in marine ecology
- These data allow us to gap fill other sources
- Rapid and synoptic data for assessing biophysical interactions at multiple spatial and temporal scales



Kelp Canopy Detection with PlanetScope Imagery

Successfully developed and validated a method for deriving kelp canopy with PlanetScope Imagery

- 120+ small satellites in orbit
- 3 m resolution at near-daily coverage starting in 2016
- Access through Planet's platform, refreshed daily
- 4-bands: blue, green, red, NIR

Cavanaugh et al., *in revision*
Remote Sensing of Environment

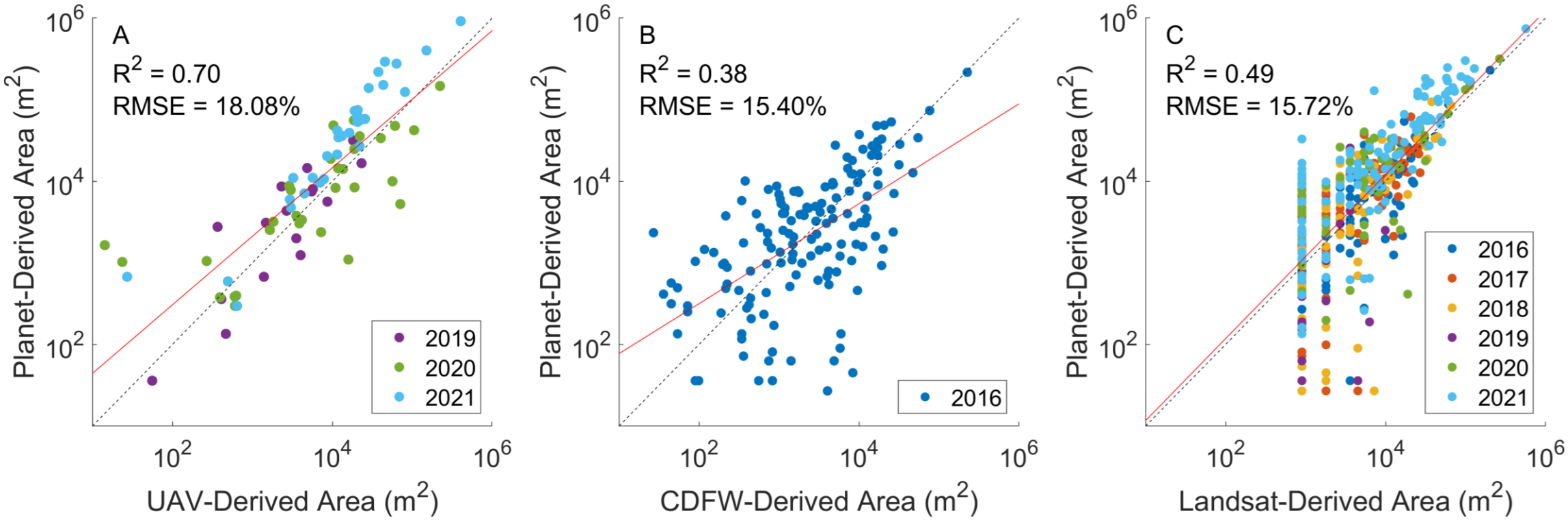
Kelp Canopy Detection with PlanetScope Imagery

Successfully developed and validated a method for deriving kelp canopy with PlanetScope Imagery

- Developed a training dataset
  - Ideal kelp and water pixels
- Trained a machine learning classifier
  - Naïve Bayes
- Aggregated classifier outputs to create spatially continuous maps of monthly kelp coverage

Cavanaugh et al., *in revision*
Remote Sensing of Environment

The derived kelp canopy maps match up well with other remote sensing datasets



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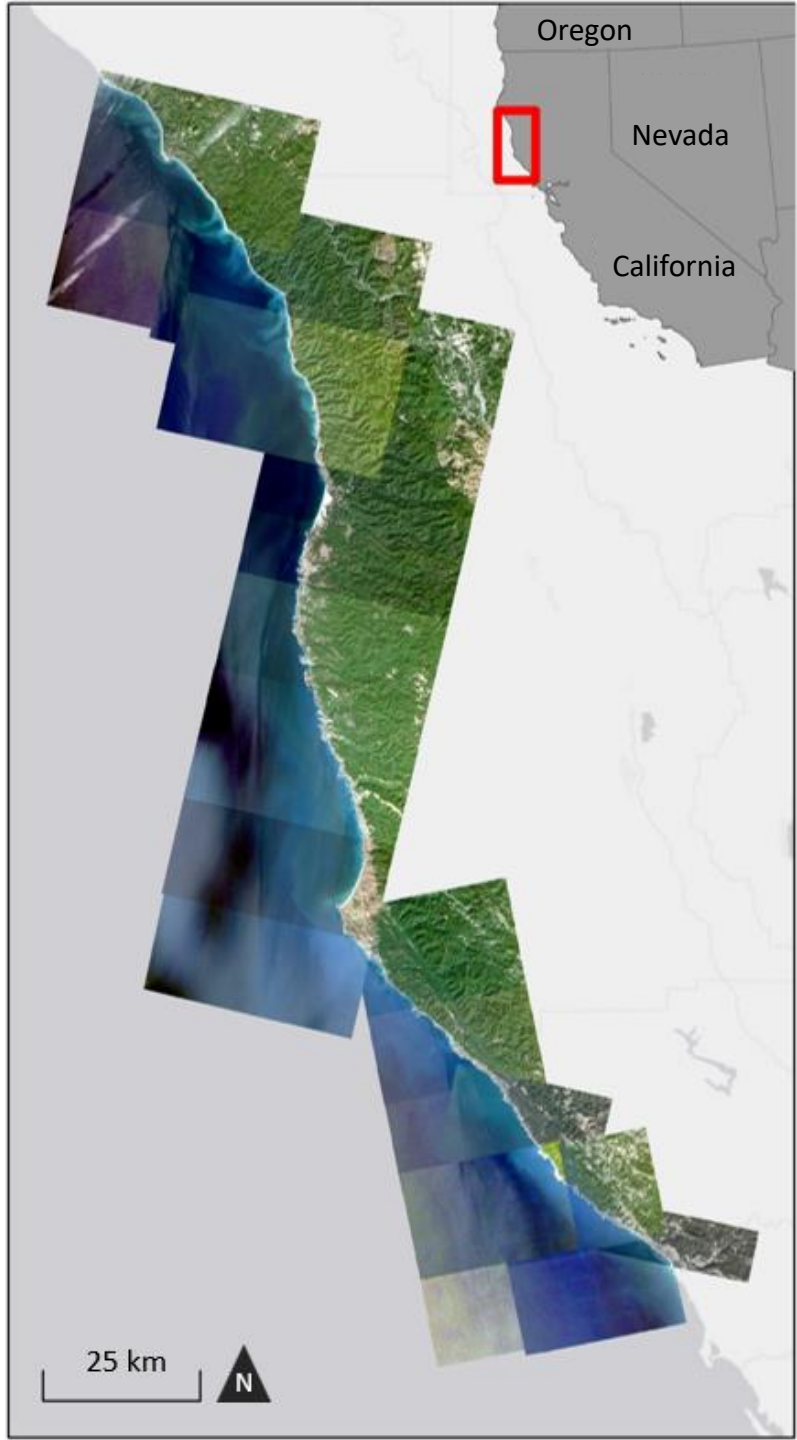
Remote Sensing of Environment

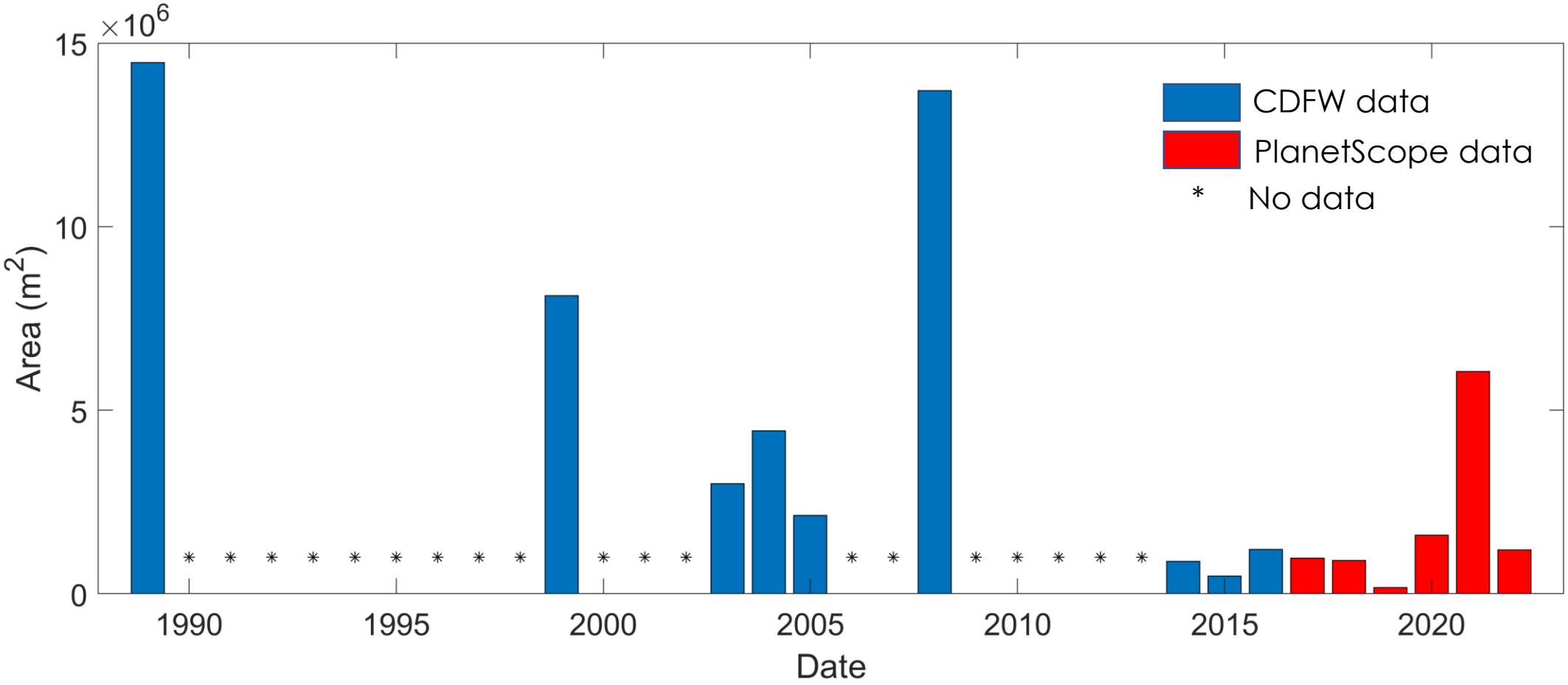
Applied method to the northern California coastline from 2016-2022

- Mendocino and Sonoma Counties
  - September and October 2016 – 2022
  - Bull kelp is an annual species and will reach maximum canopy in the fall, making September and October ideal months for classification

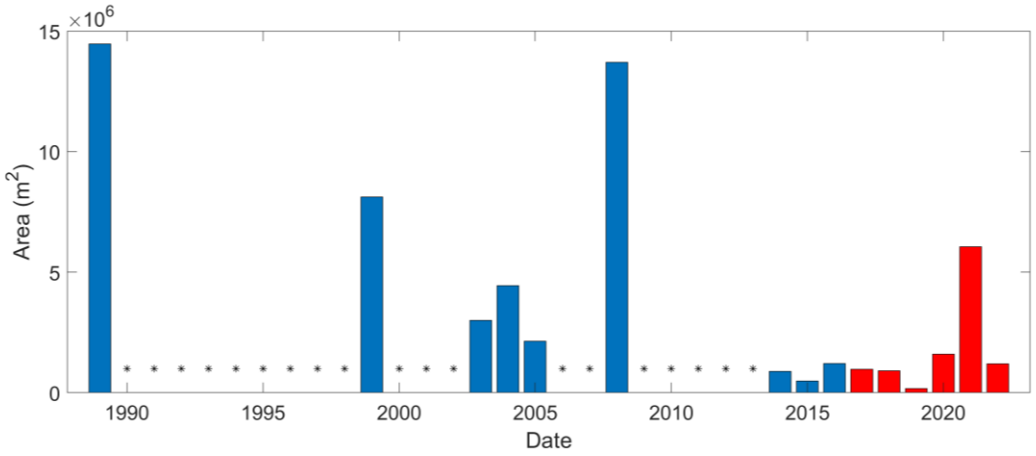


Updated kelp canopy time series

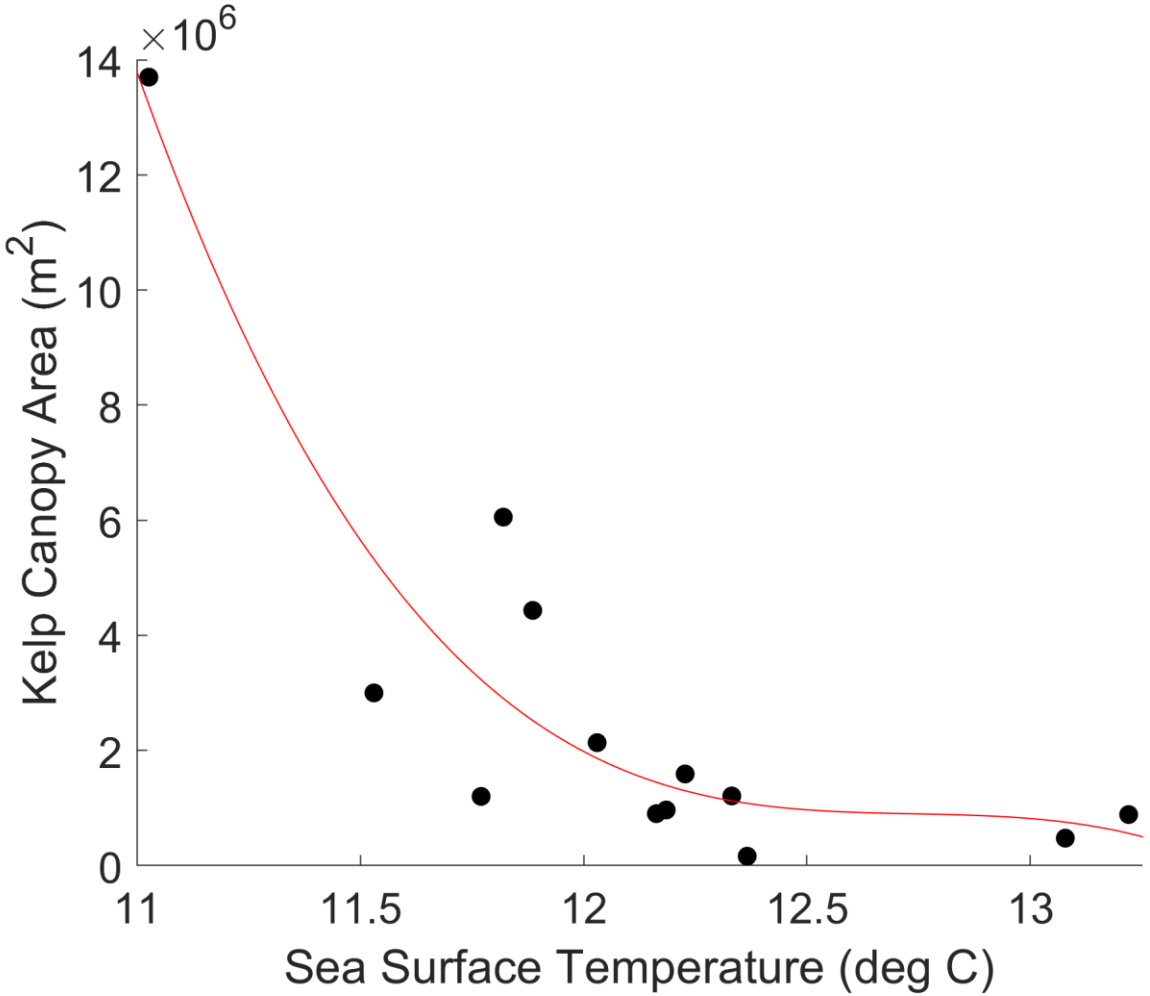
- Kelp canopy remained low from 2016 to 2020
- Signs of recovery in 2021
  - Increased to 80% of historical average from CDFW
- Declined by 80% from 2021 to 2022



Patterns in kelp canopy area are driven by factors other than temperature



There is a strong relationship between time series of kelp canopy area and mean annual sea surface temperature



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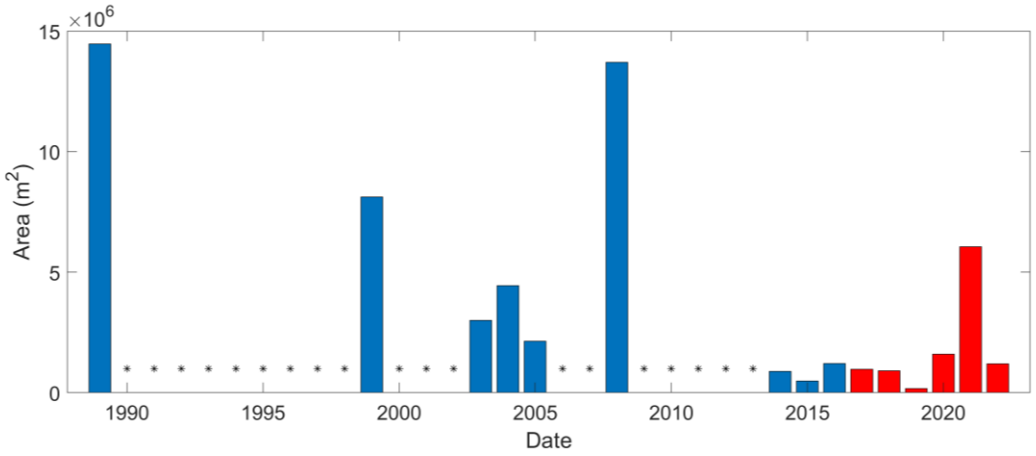

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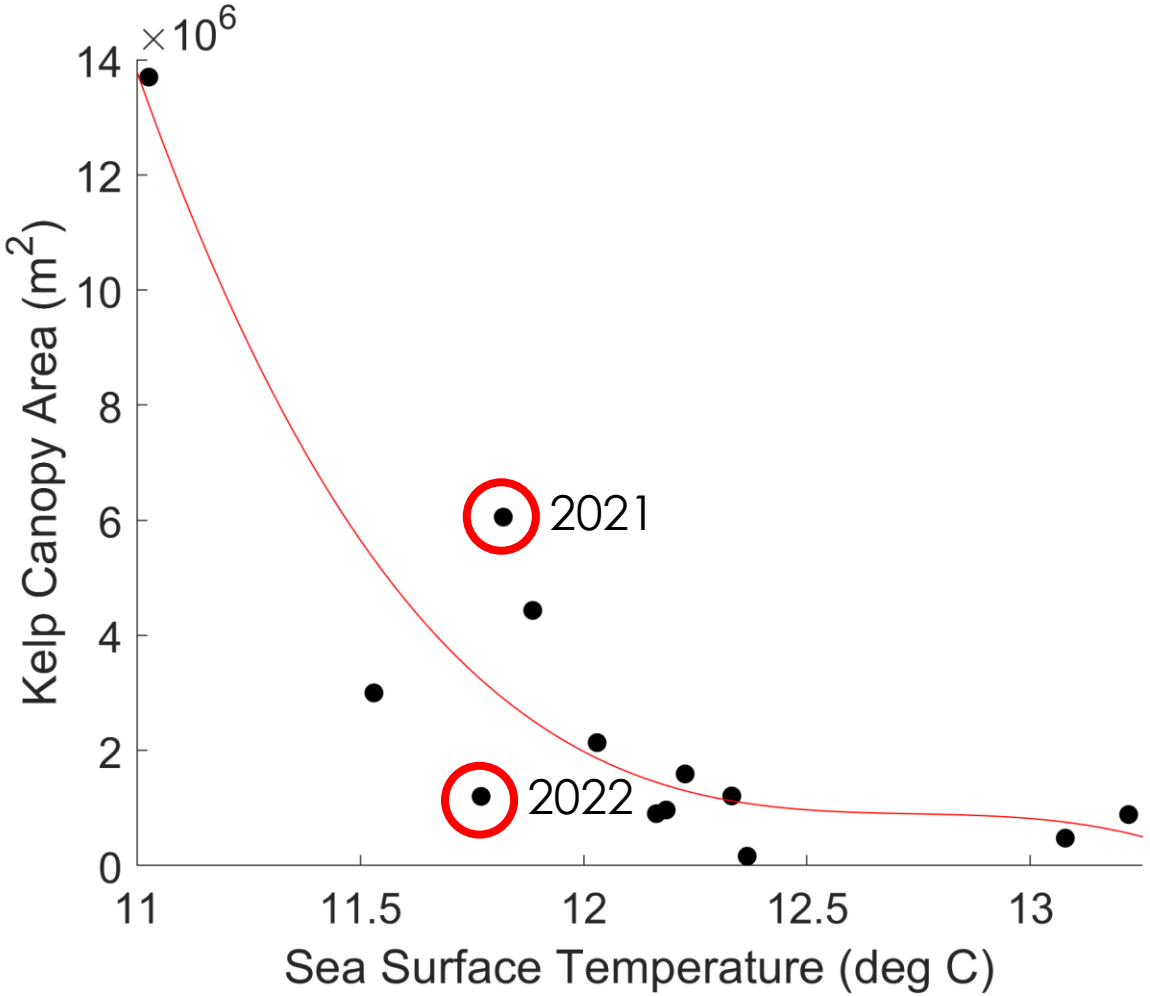

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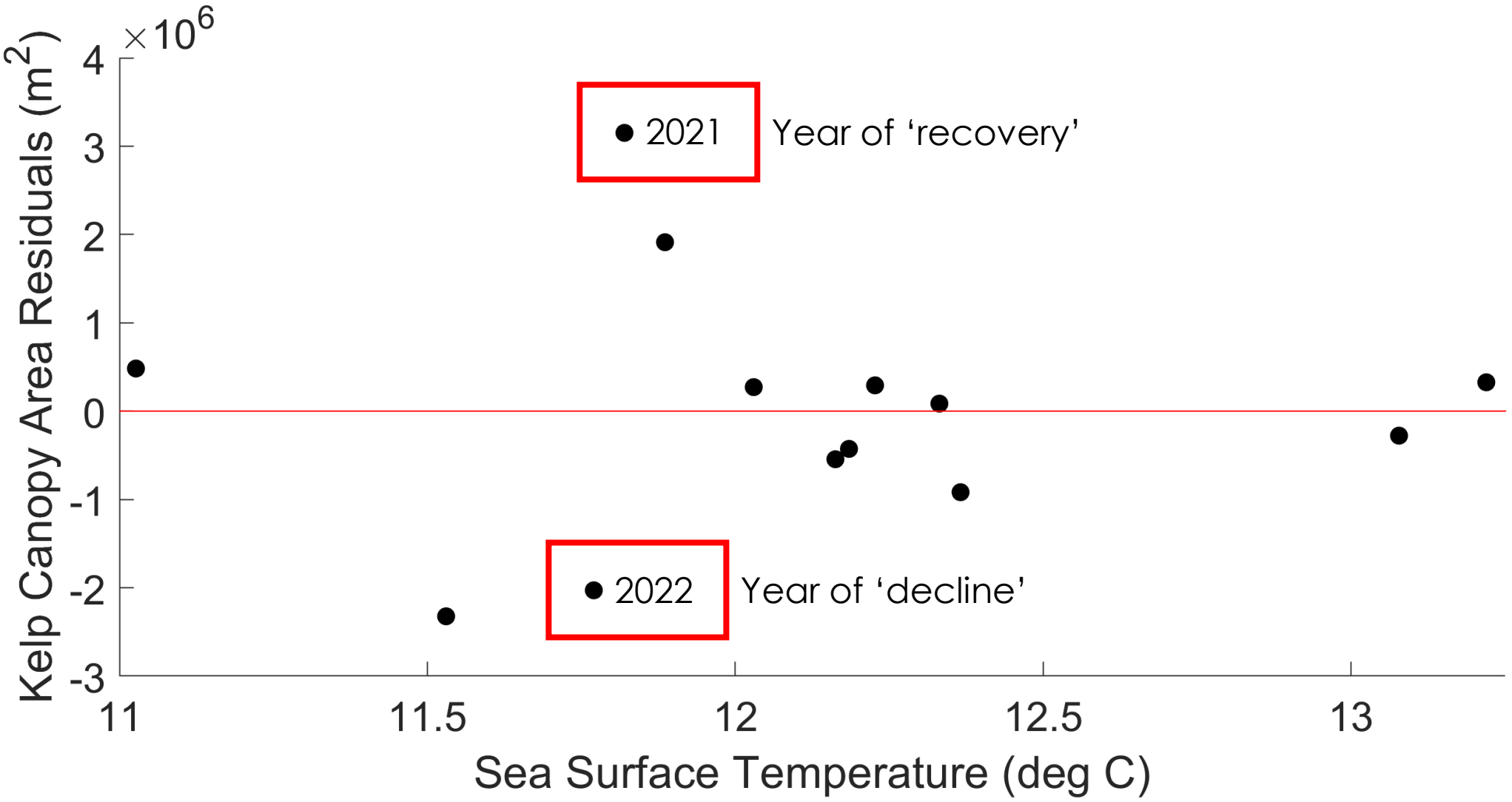
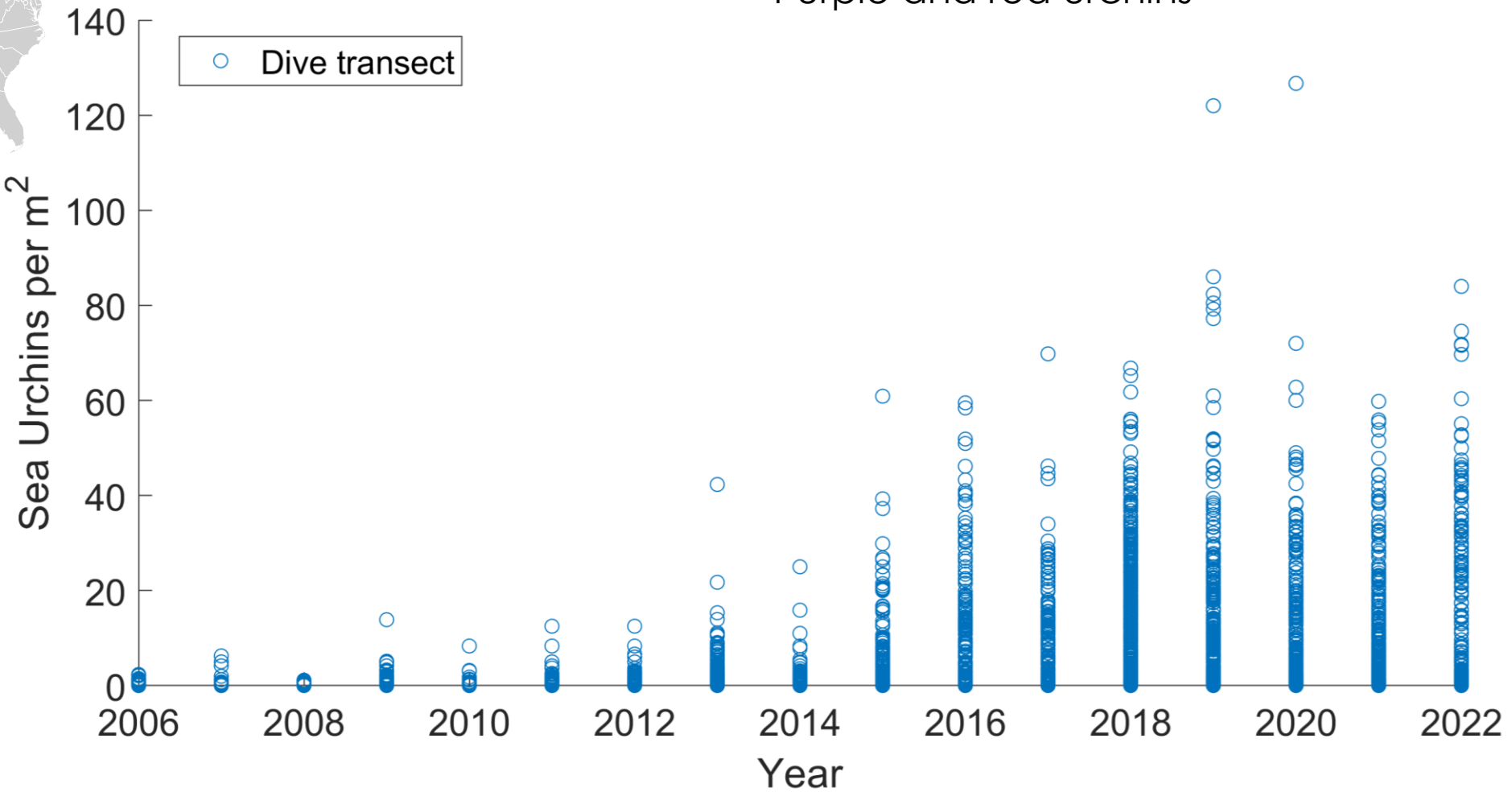


These residuals may be explained by spatial patterns in urchin populations

- Data sources
  - Laura Rogers-Bennett et al.
  - Brent Hughes et al.
  - PISCO
  - Reef Check
- Count total urchins within 30 x 2 m transects
  - Purple and red urchins



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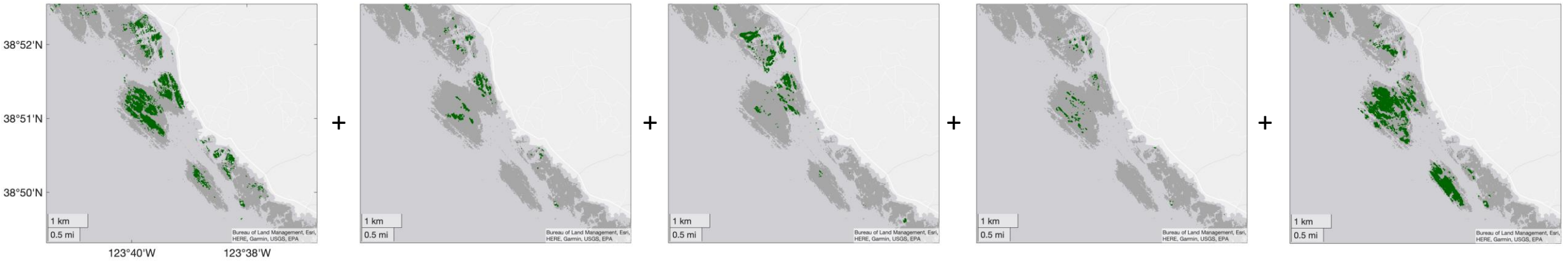
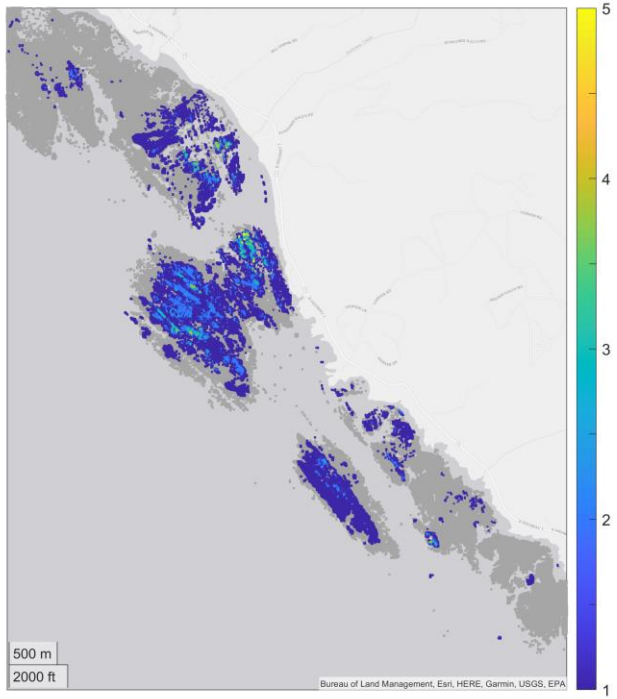
Defining and identifying bull kelp refugia in northern California

2016 + 2017 + 2018 + 2019 + 2020

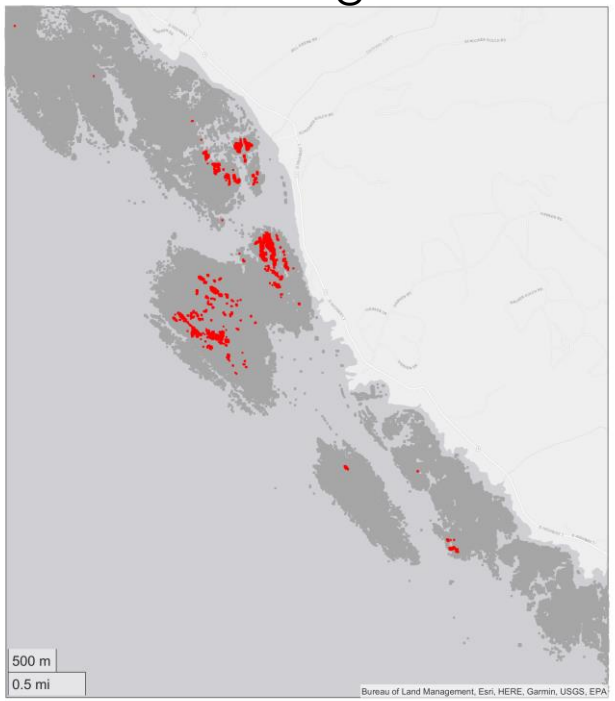


Persistence



Persistence ≥ 3

Refugia



Kelp refugia

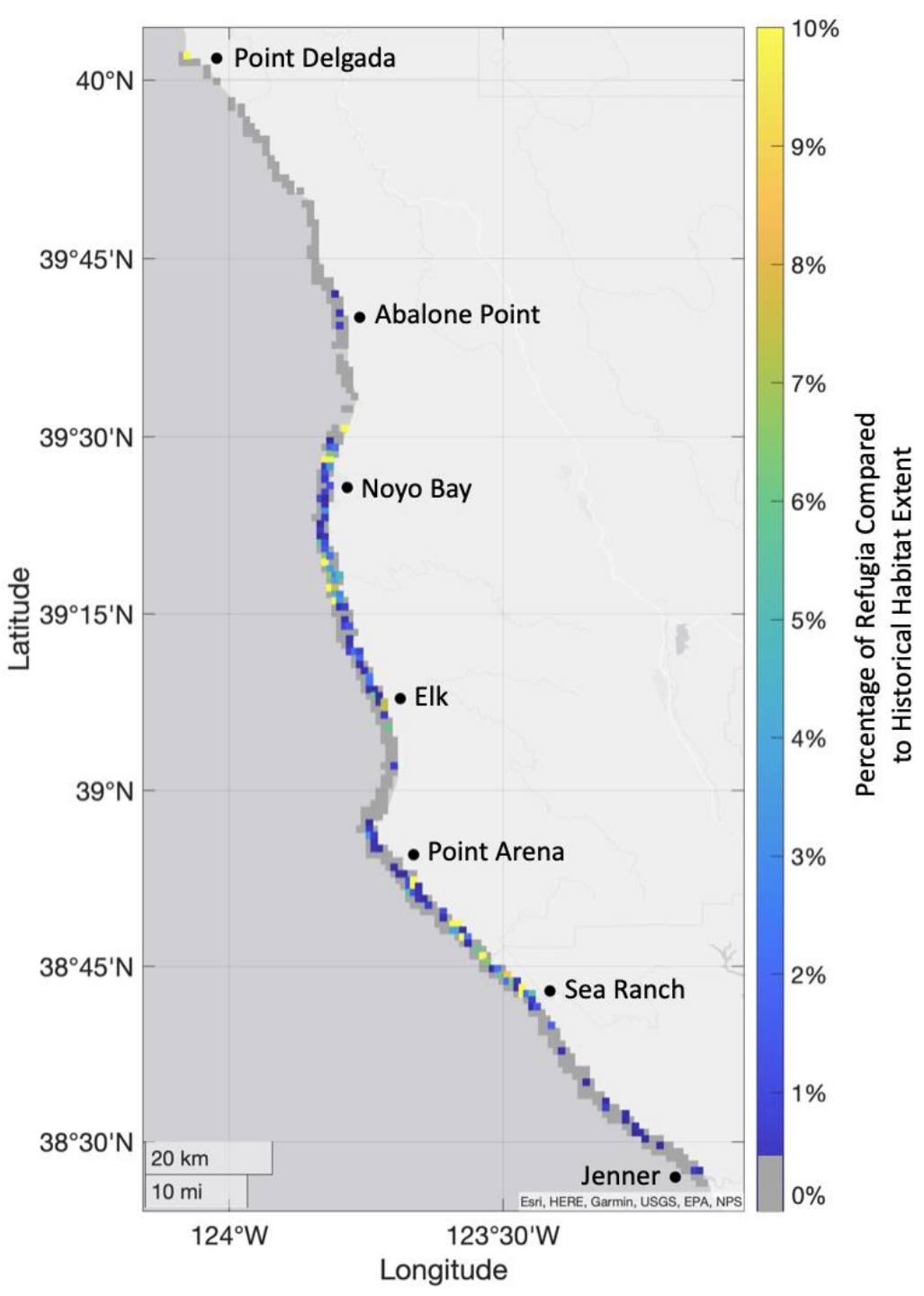
Kelp historical extent calculated from CDFW

Spatial patterns of bull kelp refugia are variable regionally

- Compared amount of refugia to any area that has been occupied by kelp canopy in the high resolution CDFW record

- Variability throughout northern California
  - Some areas contain a relatively high abundance of refugia while other areas are absent of refugia altogether

- What factors are contributing to this variability?



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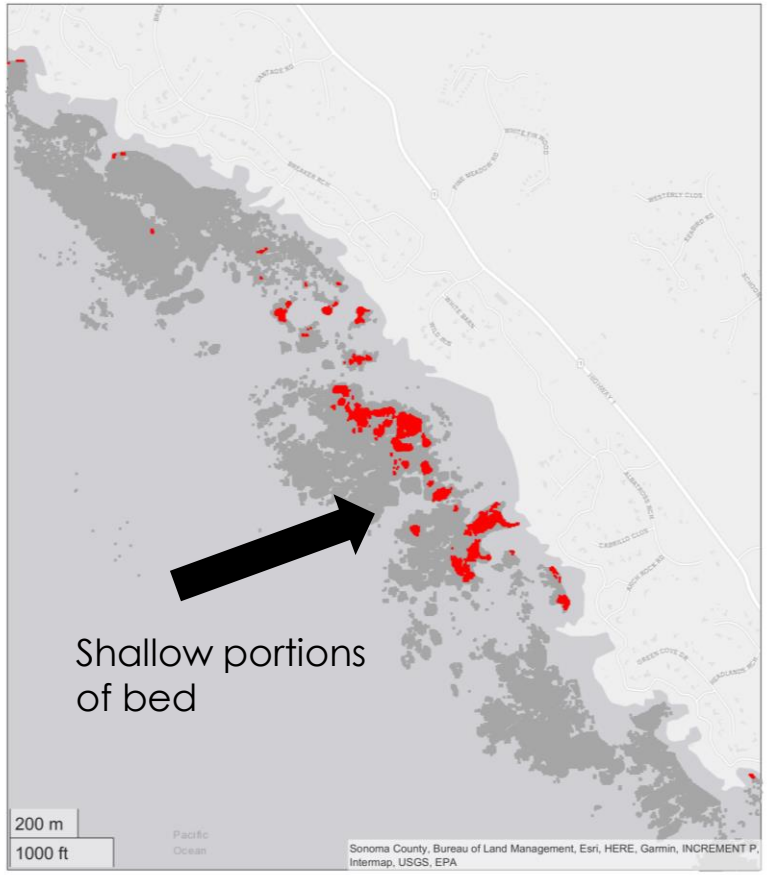
Environmental drivers of refugia

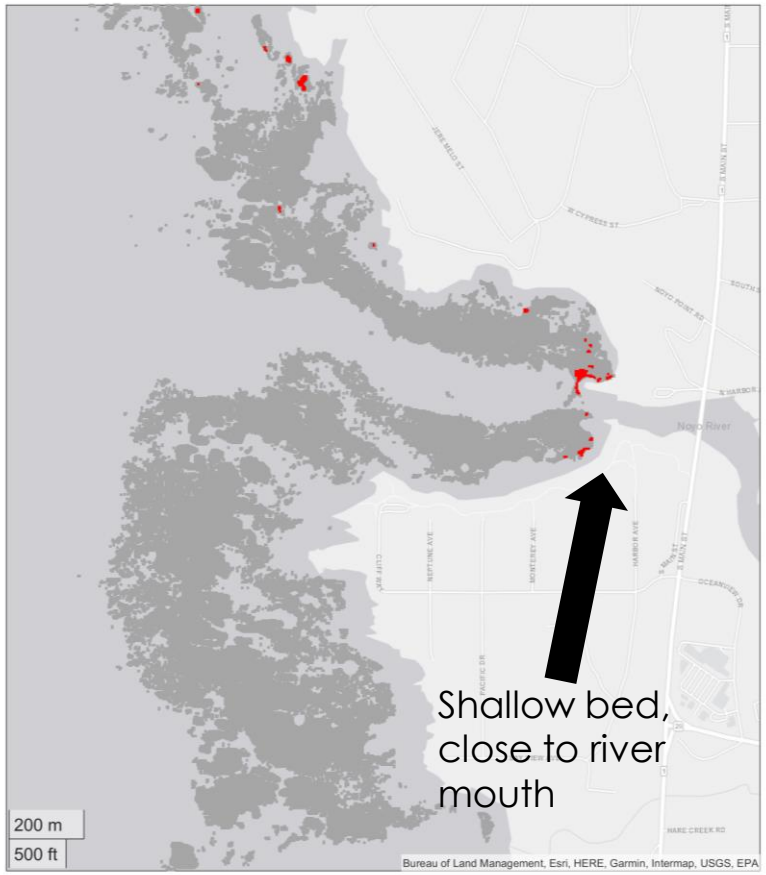
Data	Description	Source Citation
Bathymetry (depth, slope, rugosity)	A merged topobathy DEM for California	OCM Partners (2021). 2020 USGS Topobathy CoNED DEM: Northern California, https://www.fisheries.noaa.gov/inport/item/62987
Coastline features (headlands)	California headland locations provided by George et al., 2015 were used to characterize the coastline	George, D. A., Largiera, J. L., Storlazzi, P. L., & Barnard, P. L. (2015). Classification of rocky headlands in California with relevance to littoral cell boundary delineation. *Marine Geology*, *369*, 137–152.
Distance to river mouths	California stream and river locations provided by CDFW and the National Hydrography Dataset (NHD) were used to calculate distance to the nearest river mouth	https://gis.data.ca.gov/datasets/CDFW/california-streams https://www.usgs.gov/national-hydrography/national-hydrography-dataset
Sea Surface Temperature	Multi-source sea surface temperature data product	Kahru, M. (2021). California merged satellite-derived 1-km dataset. http://spg-satdata.ucsd.edu/ca1km/
Distance to edge of suitable habitat	Suitable habitat was inferred using a composite of kelp canopy from historical CDFW aerial surveys	https://wildlife.ca.gov/Conservation/Marine/Kelp/Aerial-Kelp-Surveys
Wave exposure	Coastal Data Information Program California wave model was used to estimate coastline exposure to wave action	http://cdip.ucsd.edu/

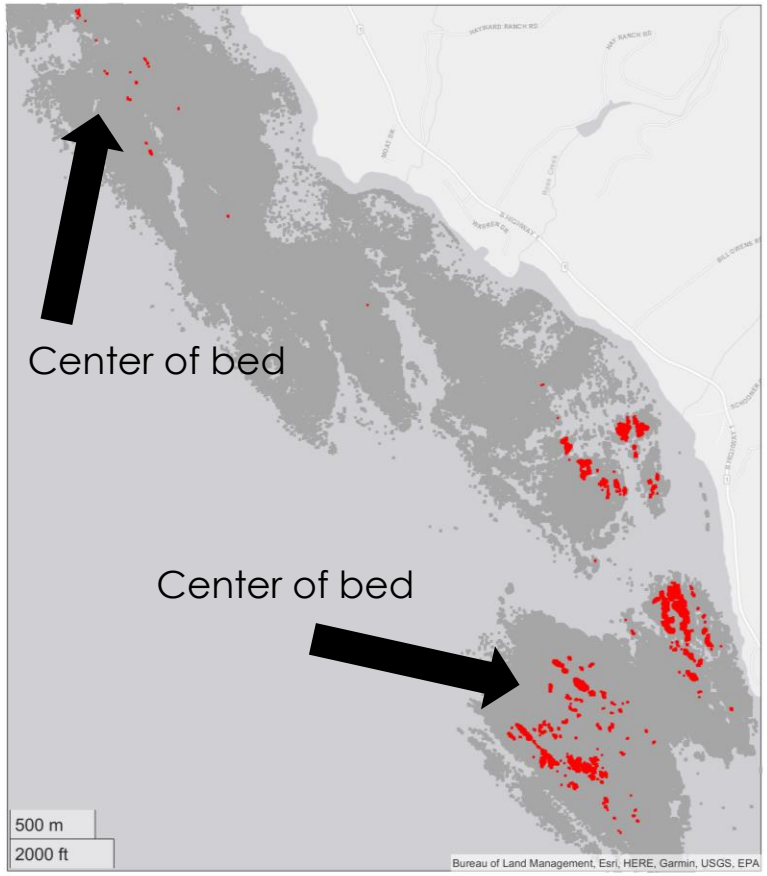
Environmental drivers of refugia

Locations of bull kelp refugia were significantly related to environmental drivers that may be unfavorable for overgrazing by sea urchins

- Shallow depths, near river mouths, near center of historical bed edge

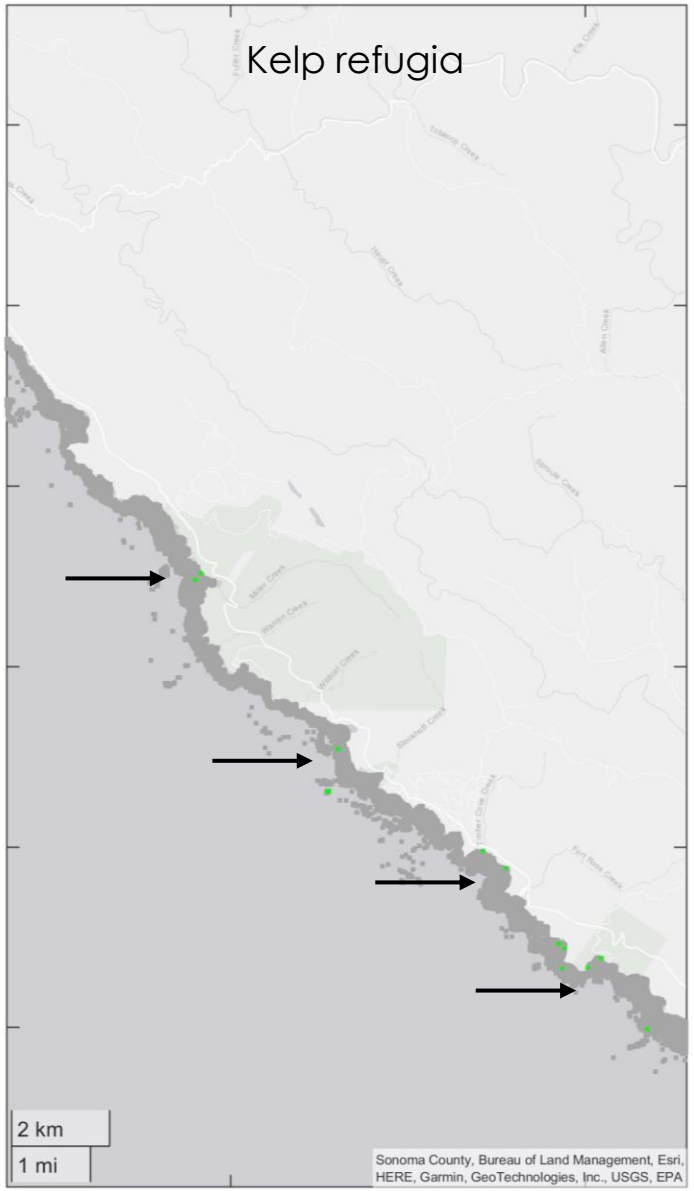


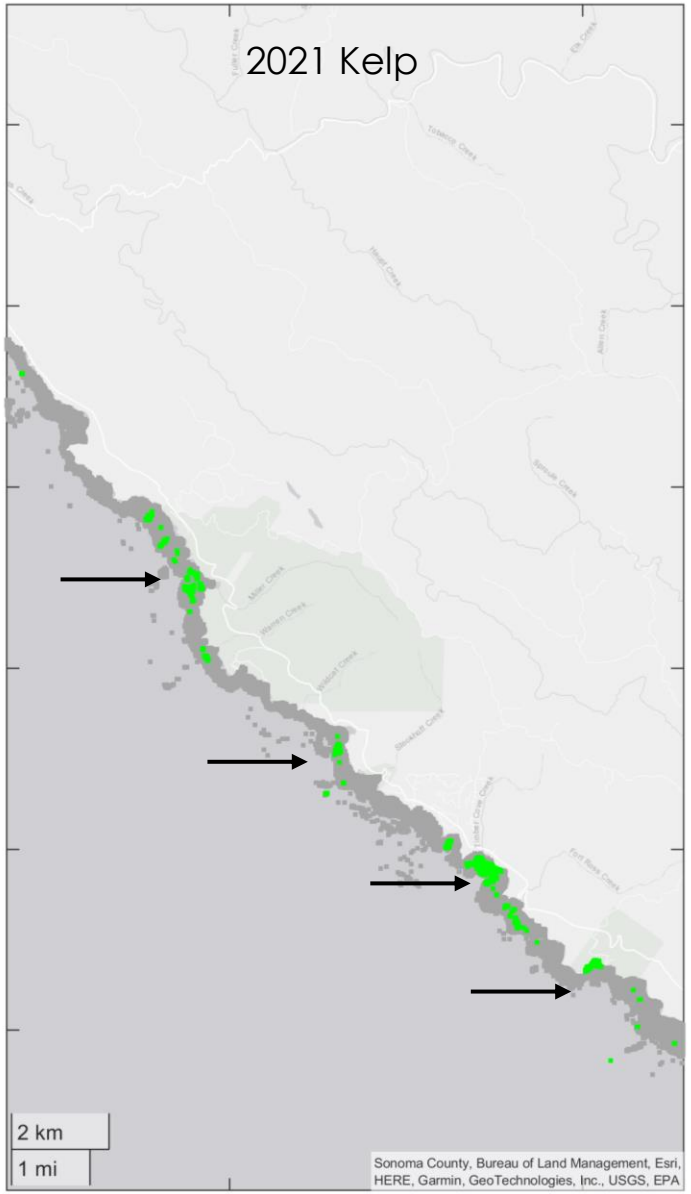


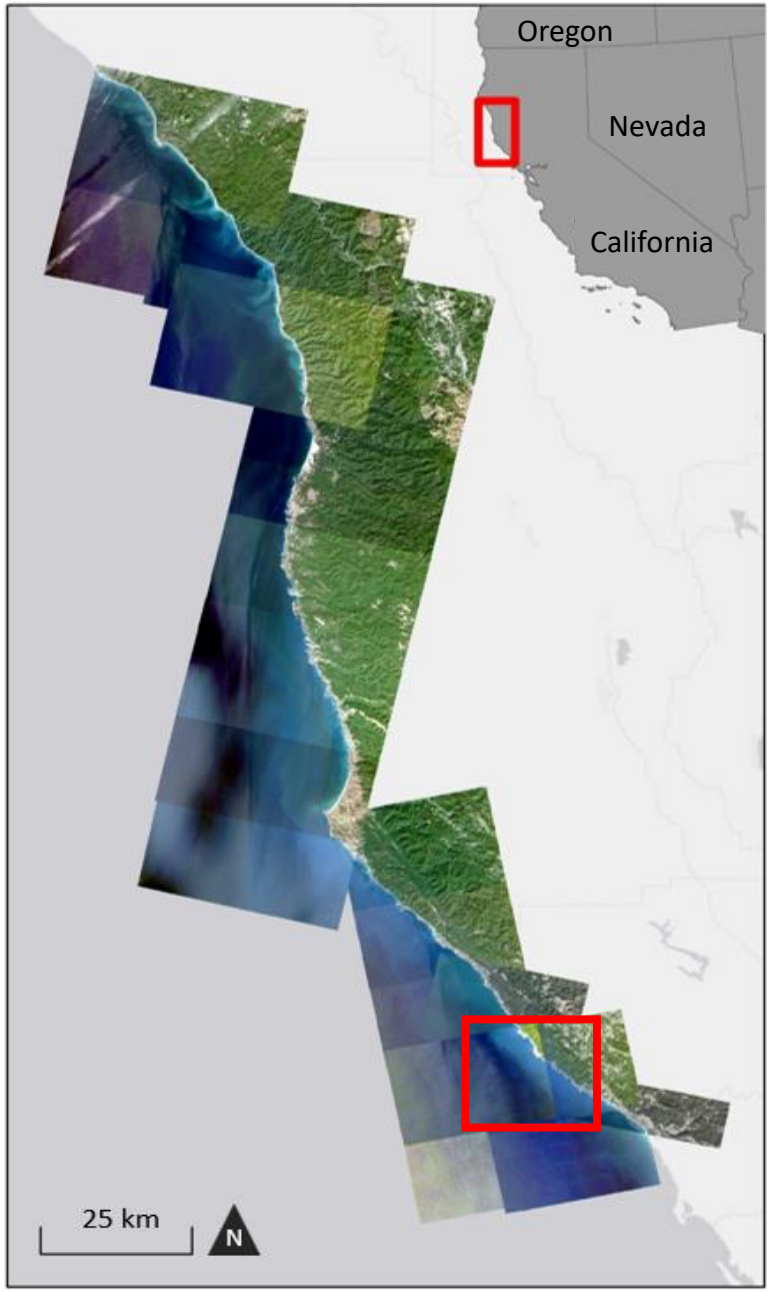


Kelp refugia Kelp historical extent

In many locations, increases in canopy area occurred around kelp refugia







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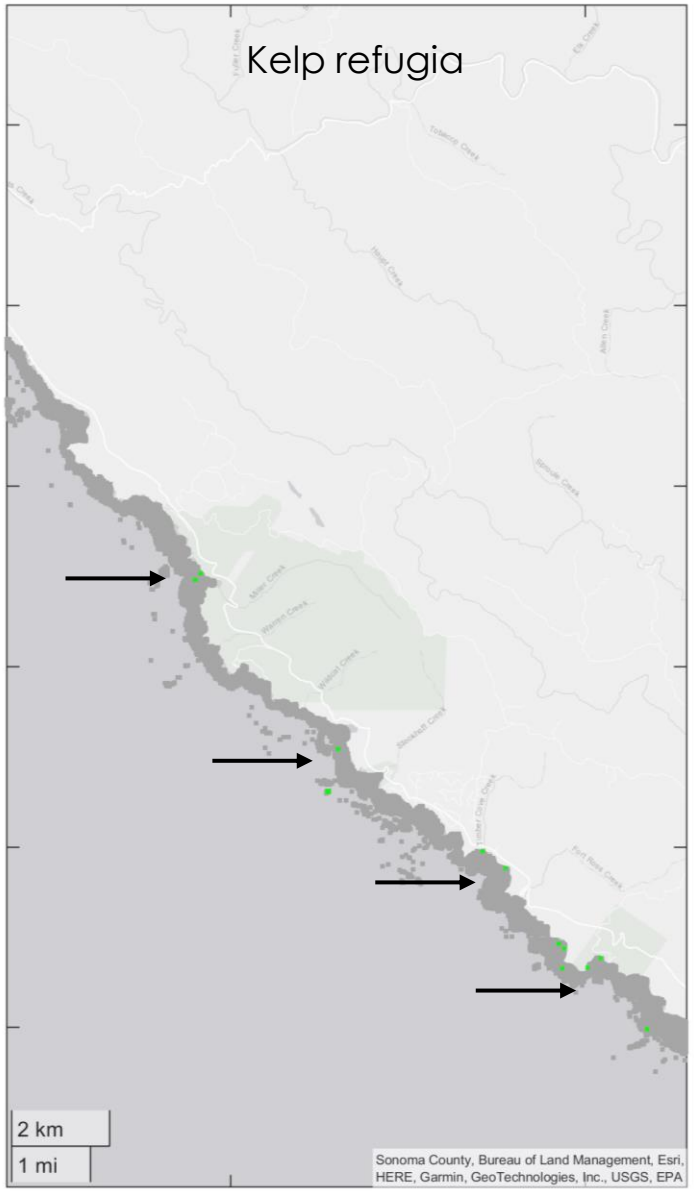
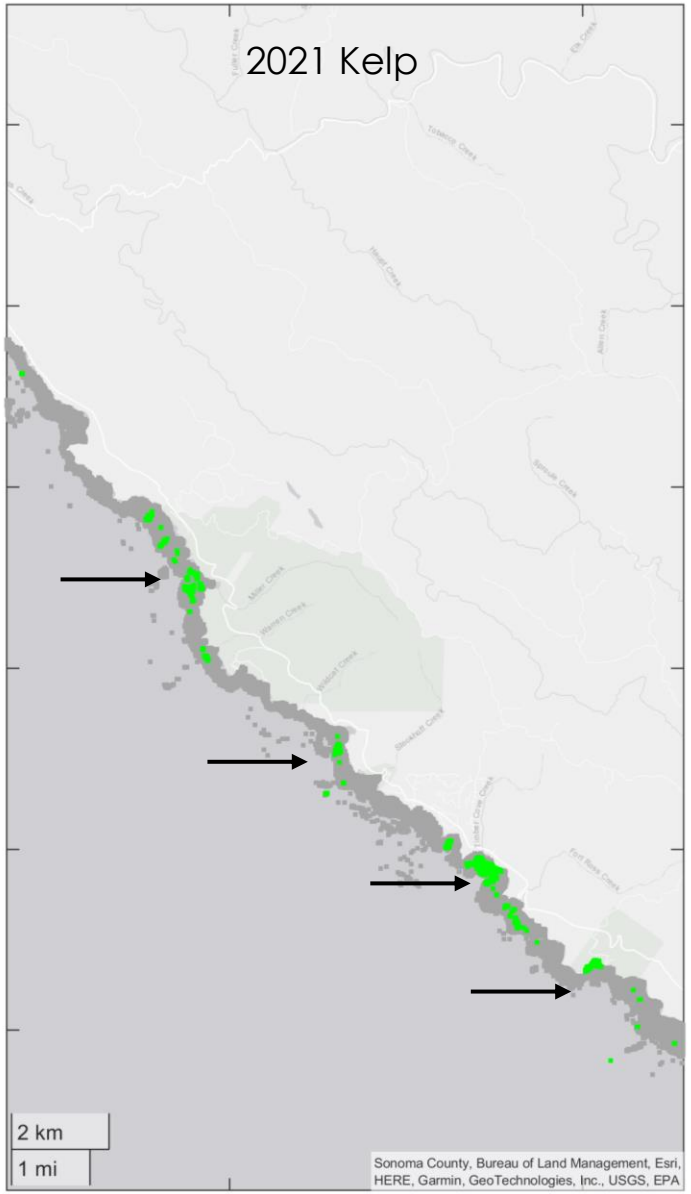


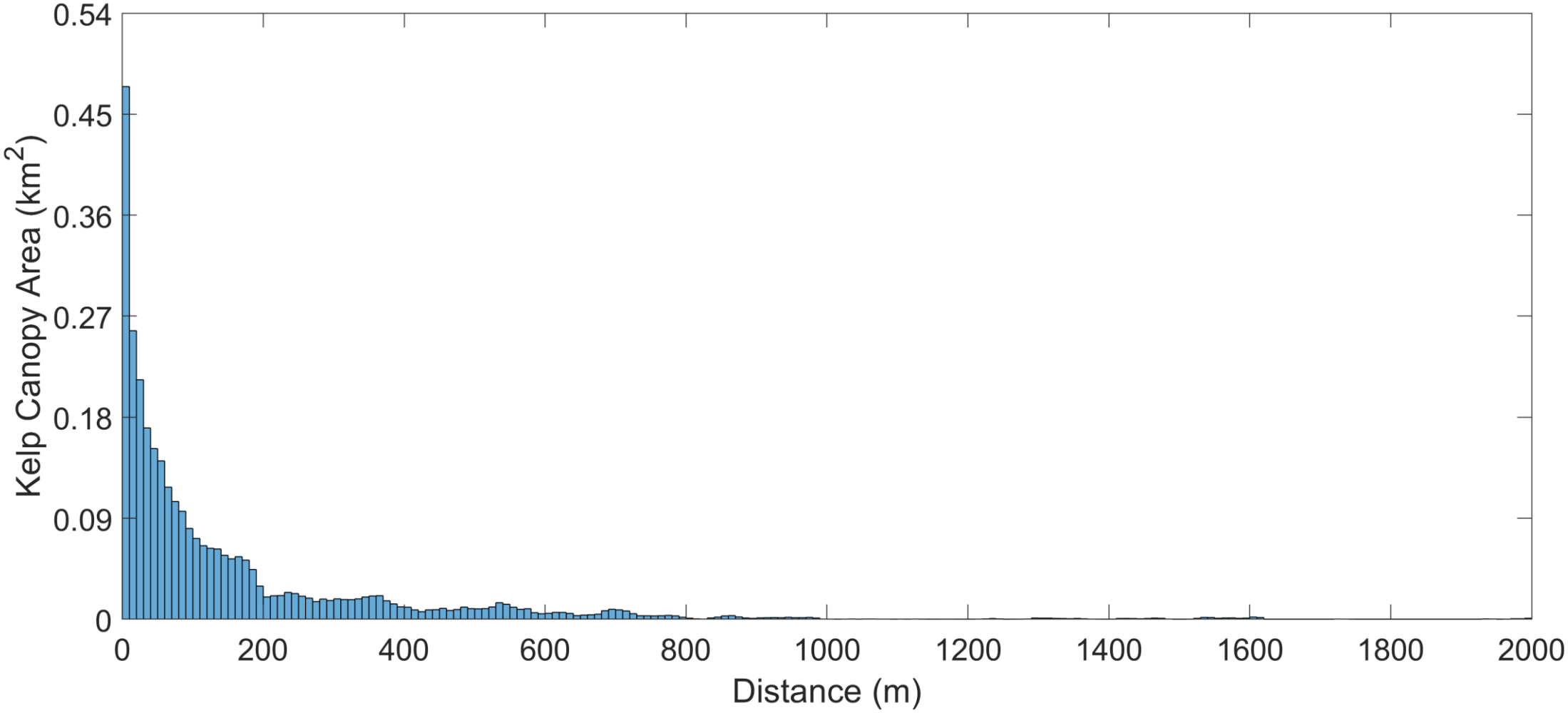


Calculating connectivity to refugia

$$I_i = d_{NN}$$

Refugia are likely important for regional recovery

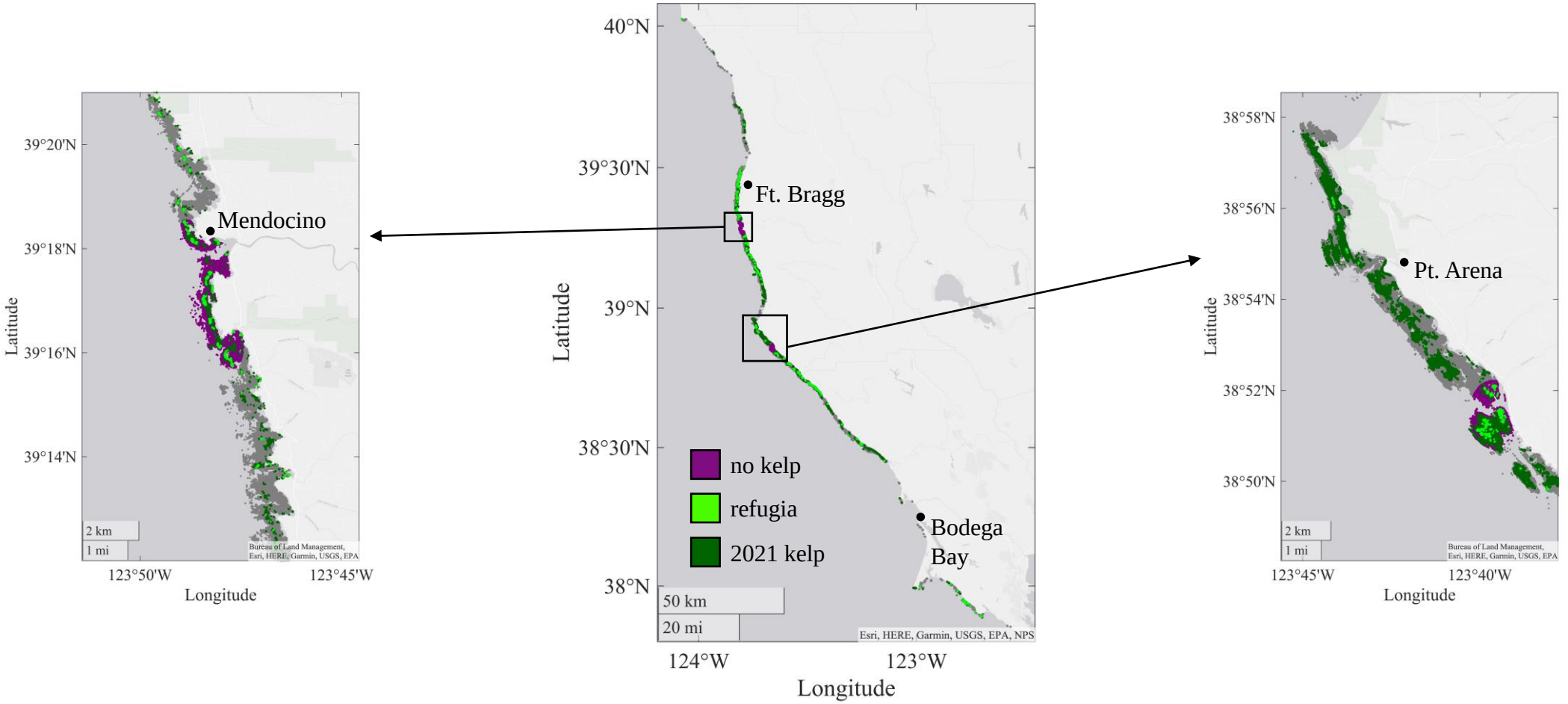
98.79% of the observed recovery occurred within 1 km of refugia locations



Where is recovery limited by grazing vs. spore source?

Connected areas (>90th percentile of distance-based connectedness) with no 2021 kelp

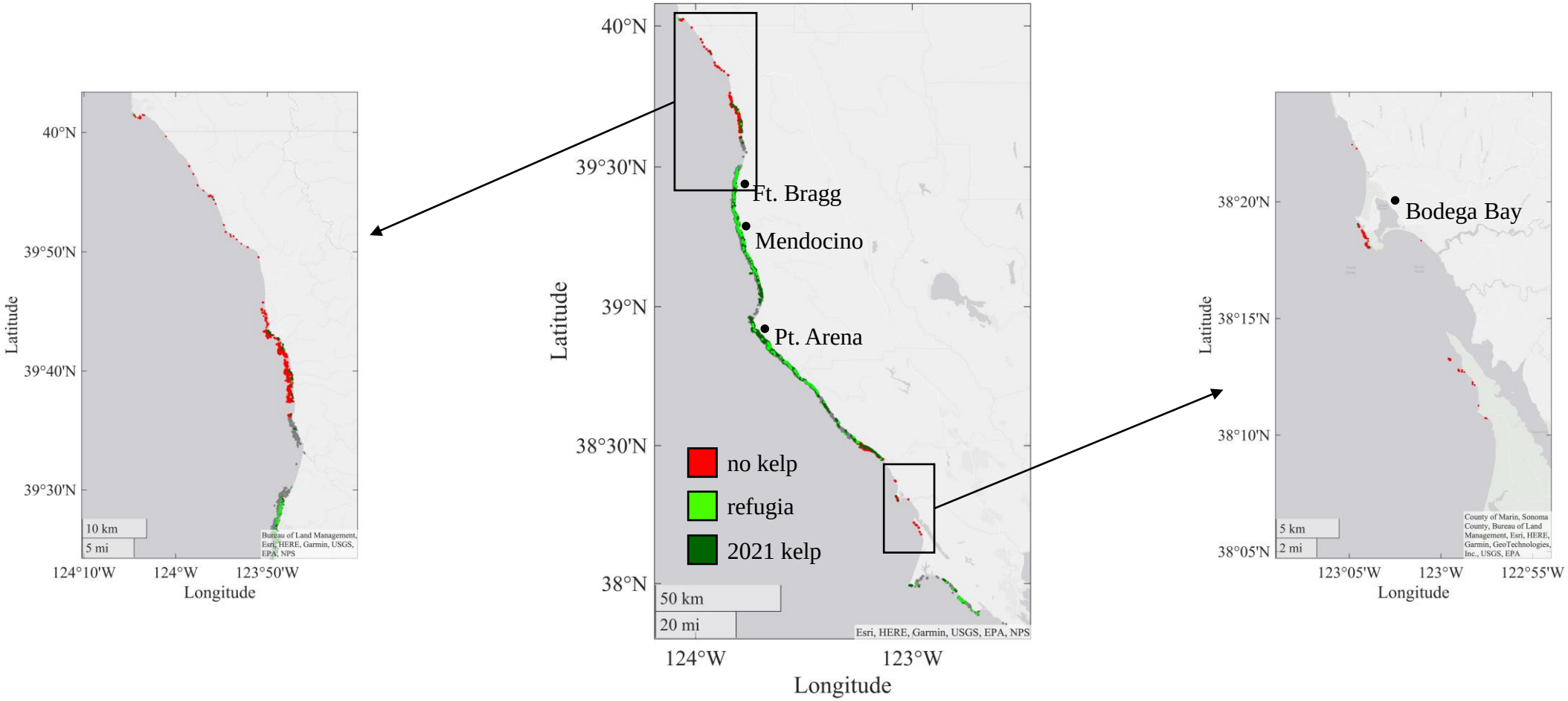
Potential urchin barrens



Where is recovery limited by grazing vs. spore source?

Isolated areas (<10th percentile of distance-based connectedness) with no 2021 kelp

Potentially spore limited



Conclusions

1. We have not observed sustained kelp recovery
2. Bull kelp persistence is spatially patchy
3. Persistence and recovery will depend on a combination of environmental drivers and connectedness to refuge populations

Thank you!

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