The Potential of High-Fidelity Spatial, Spectral, Temporal, and Radiometric Sensors to Advance Aquatic Remote Sensing Beyond Chlorophyll

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NASA SARP Participants

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TARGETED OBSERVABLE	SCIENCE/APPLICATIONS SUMMARY	CANDIDATE MEASUREMENT APPROACH	Designated	Explorer	Incubation
Aerosols	**Aerosol properties, aerosol vertical profiles, and cloud properties** to understand their direct and indirect effects on climate and air quality	Backscatter lidar and multi-channel/multi-angle/polarization imaging radiometer flown together on the same platform	x		
Clouds, Convection, & Precipitation	**Coupled cloud-precipitation state and dynamics** for monitoring global hydrological cycle and understanding contributing processes	Radar(s), with multi-frequency passive microwave and sub-mm radiometer	x		
Mass Change	**Large-scale Earth dynamics** measured by the changing mass distribution within and between the Earth's atmosphere, oceans, ground water, and ice sheets	Spacecraft ranging measurement of gravity anomaly	x		
Surface Biology & Geology	**Earth surface geology and biology,** ground/water temperature, snow reflectivity, active geologic processes, vegetation traits and algal biomass	Hyperspectral imagery in the visible and shortwave infrared, multi- or hyperspectral imagery in the thermal IR	x		
Surface Deformation & Change	**Earth surface dynamics** from earthquakes and landslides to ice sheets and permafrost	Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction	x		
Greenhouse Gases	**CO_2 and methane fluxes and trends,** global and regional with quantification of point sources and identification of source types	Multispectral short wave IR and thermal IR sounders; or lidar**		x	
Ice Elevation	**Global ice characterization** including elevation change of land ice to assess sea level contributions and freeboard height of sea ice to assess sea ice/ocean/atmosphere interaction	Lidar**		x	
Ocean Surface Winds & Currents	**Coincident high-accuracy currents and vector winds** to assess air-sea momentum exchange and to infer upwelling, upper ocean mixing, and sea-ice drift.	Radar scatterometer		x	

"Thriving on our Changing Planet"

Ecosystem Change

Surface Biology & Geology

"…and algal biomass"

NO! Don't stop there!

Decadal Survey 2017

What do Managers Need from Optical Remote Sensing in Aquatic Ecosystems?

- Status, Condition and Trend & Anomalies:
  - **Status (survey, classify and map)**
    - **what is where? (=99%of current remote sensing effort)**
      - **(is it absent when it should be present) or**
      - **(is it present when it should be absent?)**
  - **Condition:**
    - **is it healthy?, is it stable?**
    - **Is it stressed?**
  - **Trend:**
    - **Is it getting worse or is it improving?**
      - **Remote Sensing can do hind casting and now casting**
      - **Model data fusion and data assimilation needed for forecasting**
  - **Anomalies:**
    - **Normal (to be expected) or exceptional (indicating exceptional change from before? E.g. climate change indication?)**

Courtesy of Arnold Dekker

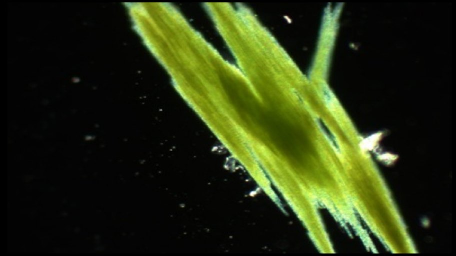
EBV class	EBV	Habitat type							
		Wetland vegetation	Benthic communities			Pelagic organisms			
		Mangrove/ salt marsh	Seagrass	Macroalgae	Coral	Phytoplankton	HAB	Fish, Zoo-plankton	Apex predator
Genetic composition	Population genetic diversity								
Species populations	Distribution								
	Abundance								
	Size/vertical distribution								
Species traits	Pigments							NA	NA
	Phenology								
Community composition	Taxonomic diversity								
Ecosystem structure	Functional type								
	Fragmentation/ heterogeneity					Routine use for open ocean			
Ecosystem function	Net primary production							NA	
	Net ecosystem production						NA	NA	NA

Legend
Unproven
Demonstrated limited cases
Routine use
Habitat model required

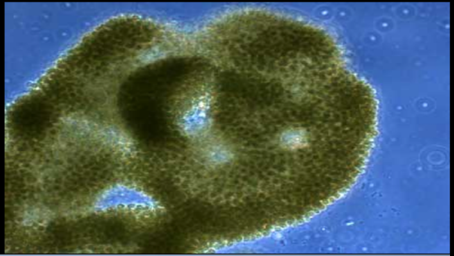
Phytoplankton Food Quality Index
PFTs to Identify HABs

Muller-Karger et al. 2018, Ecol. Appl. 28: 749-760

Optically similar genera are functionally different (toxic vs. non-toxic, type of toxins, etc)

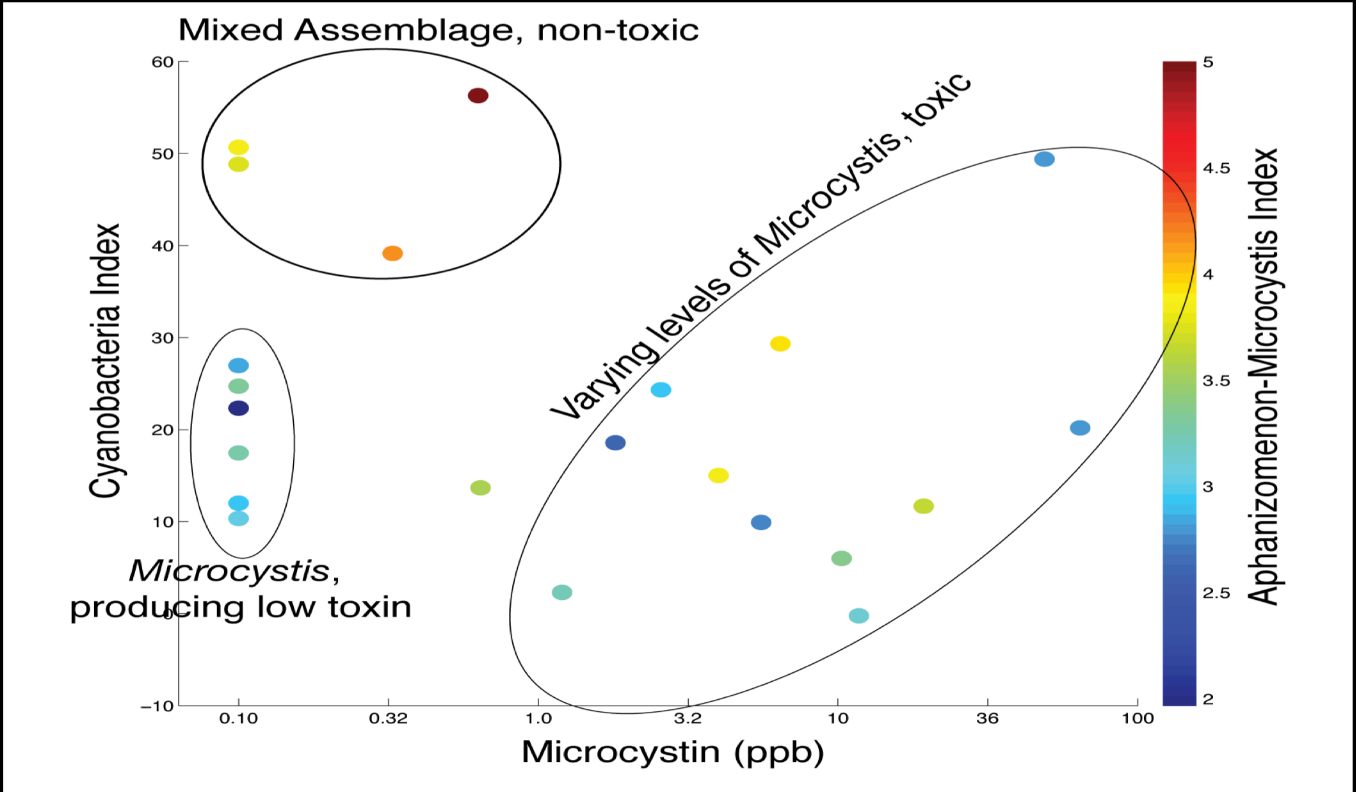


Aphanizomenon flos-aquae



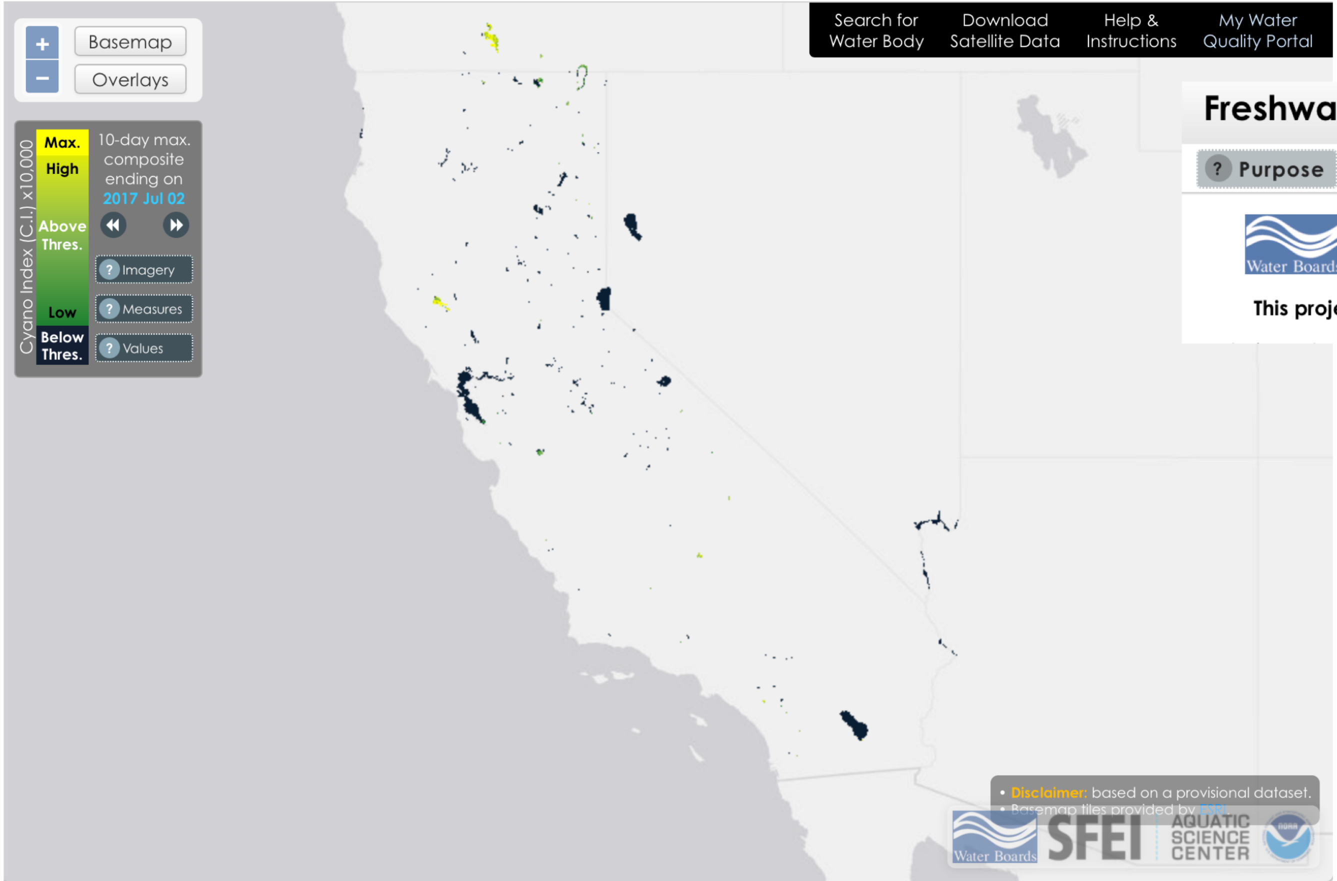
Microcystis spp.

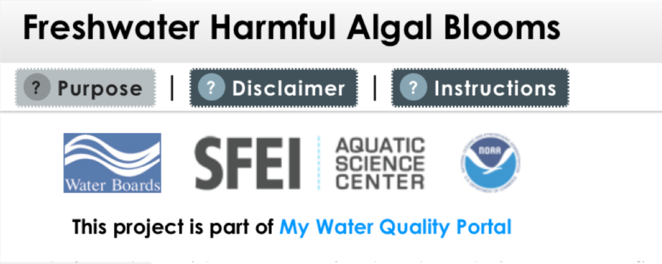
Predicting Toxic Blooms



Kudela et al. 2015, Remote Sens. Env.

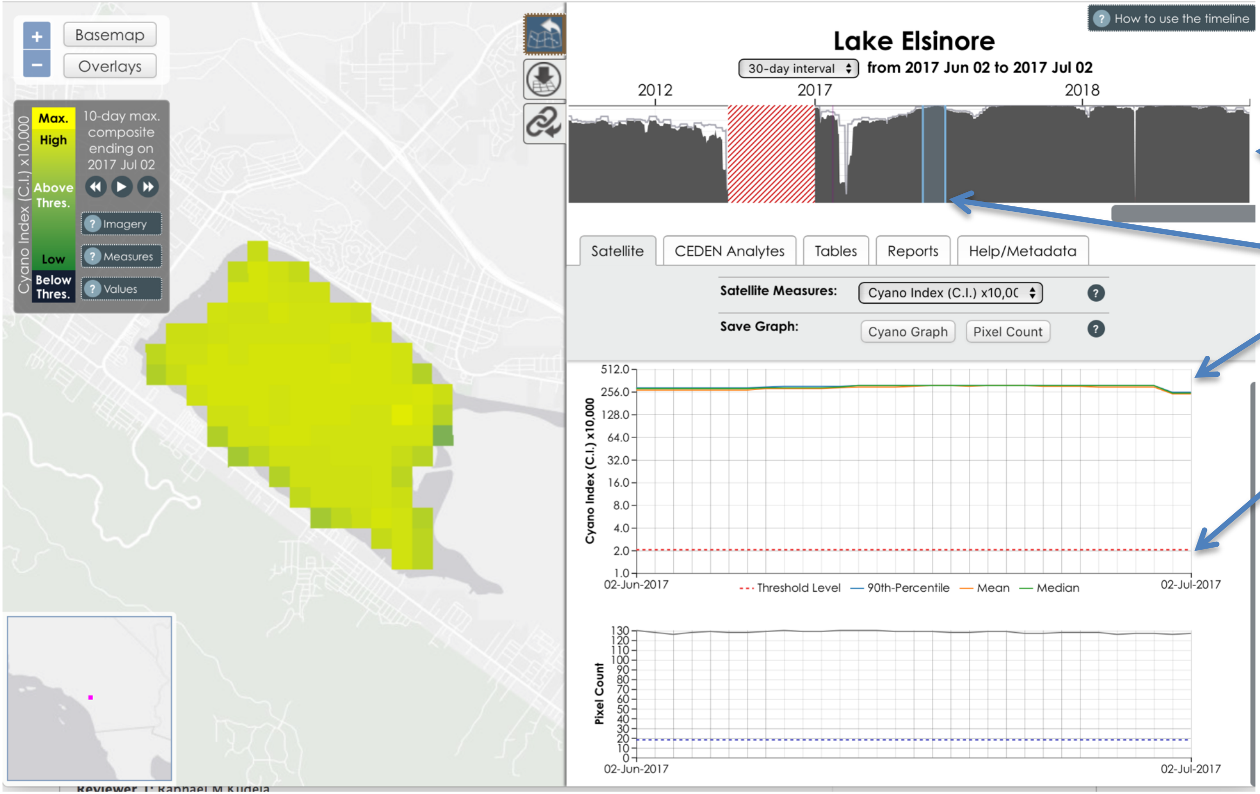
Scaling to Regional Analyses





https://cchab.sfei.org/

Scaling to Regional Analyses



Above threshold for all of 2017 (and 2018)

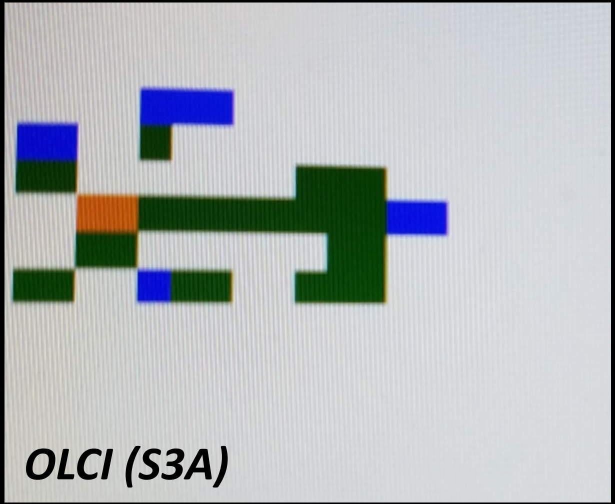
30-day window, June 2, 2017

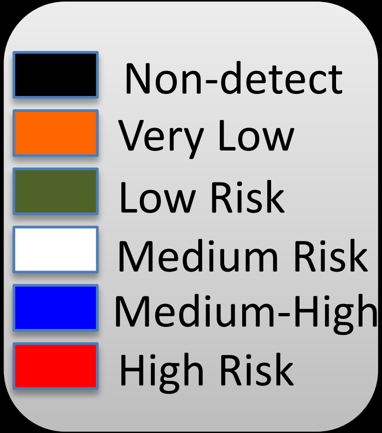
Threshold for concern

https://cchab.sfei.org/

Lake Elsinore CA, June 2, 2017

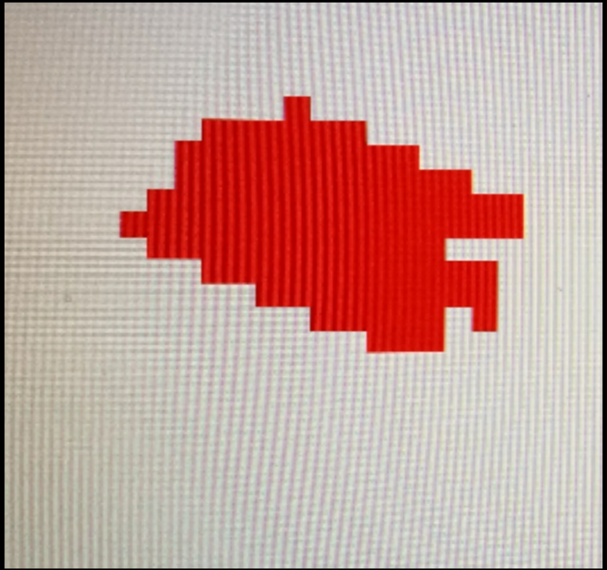
AVIRIS + MASTER → L8 OLI + S3A/OLCI → Toxin Index





Reported Toxins: <1.5 ppb

Lake Elsinore CA, June 28, 2017



- Non-detect
- Very Low
- Low Risk
- Medium Risk
- Medium-High
- High Risk

Reported Toxins: >10,000 ppb

M

In the US ... ed number of death...

"All the News That's Fit to Print"

The New York Times

National Edition
Clouds and sunshine. Highs in upper 80s to 90s. Mostly cloudy west tonight. Clear east. Lows in 60s to mid-70s. Thundershowers tomorrow. Details, SportsSunday, Page 10.

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Russian Sought Potent Friends Beyond N.R.A.

Scions and Lawmakers Among Connections

*This article is by **Matthew Rosenberg, Mike McIntire, Michael LaForgia, Andrew E. Kramer** and **Elizabeth Dias.***

WASHINGTON — Twelve days after a young Russian gun-rights activist gained access to some of America's most prominent conservatives, at an elegant dinner near the Capitol, a Republican operative was eager to keep the momentum going.

Maria Butina

In a February 2017 email, the operative, Paul Erickson, proposed another "U.S./Russia friendship" dinner. He noted that the activist, Maria Butina, who now is accused of being a covert Russian agent, was making an "ever-expanding circle of influential friends."

Ms. Butina, he wrote in the email, had just met Susan Eisenhower, the granddaughter of President Dwight D. Eisenhower, during a visit to Gettysburg College in Pennsylvania. The Russian woman had also gotten to know the ex-wife of a supermarket heir, who had endowed an institute dedicated to furthering American-Russian relations, and the "silky smooth" former Russian diplomat who ran it.

THE CONSEQUENCES OF INACTION

GEORGE STEINMETZ FOR THE NEW YORK TIMES

This week's issue of The New York Times Magazine is dedicated to a single article, "Losing Earth" by Nathaniel Rich, which chronicles the early efforts of scientists, activists and politicians to raise the alarm about the dangers of climate change, and shows how close they came to solving it. Above, Lake Tai, China, where global warming has helped algae blooms to flourish.

DATA ON MOTHERS REVEAL SCHISMS ACROSS AMERICA

EDUCATION A TOP GAUGE

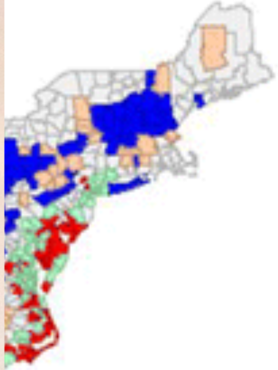
Children's Opportunities Can Hinge on the Mothers' Ages

By QUOCTRUNG BUI and CLAIRE CAIN MILLER

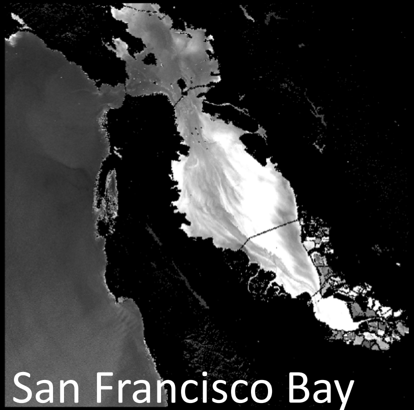
Becoming a mother used to be seen as a unifying milestone for women in the United States. But a new analysis of four decades of births shows that the age that women become mothers varies significantly by geography and education. The result is that children are born into very different family lives, heading for diverging economic futures.

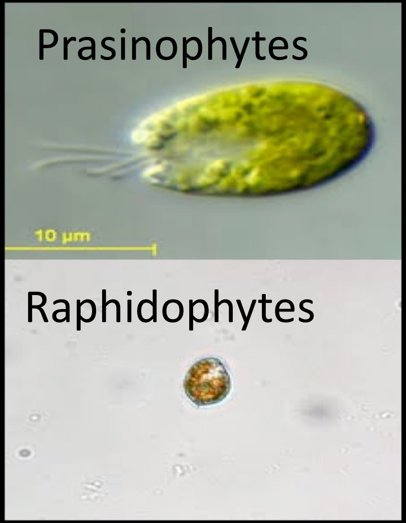
First-time mothers are older in big cities and on the coasts, and younger in rural areas, the Great Plains and the South. In New York and San Francisco, their average age is 31 and 32. In Todd County, S.D., and Zapata County, Tex., it's half a generation earlier, at 20 and 21, according to the analysis, which was of all birth certificates in the United States since 1985 and nearly all for the five years prior. It was conducted for The New York Times by Caitlin Myers, an economist who studies reproductive policy at Middlebury College, using data from the National Center for Health Statistics.

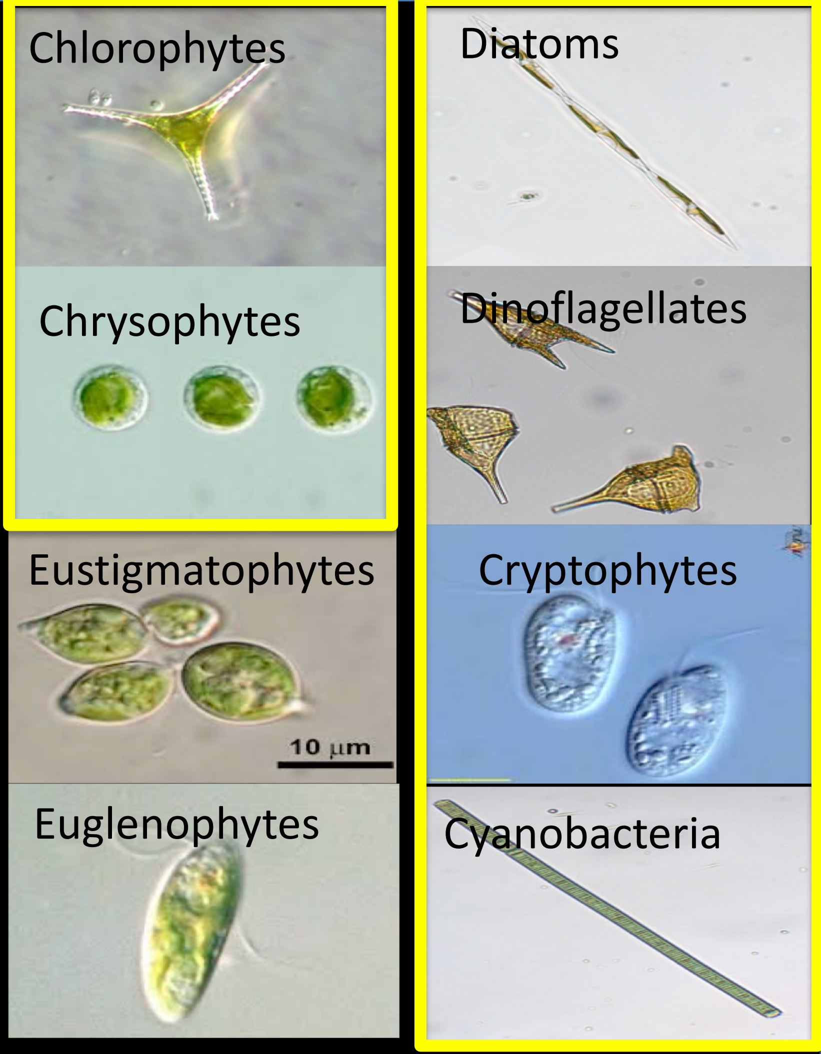
The difference in when women start families cuts along many of



4:41 DOI





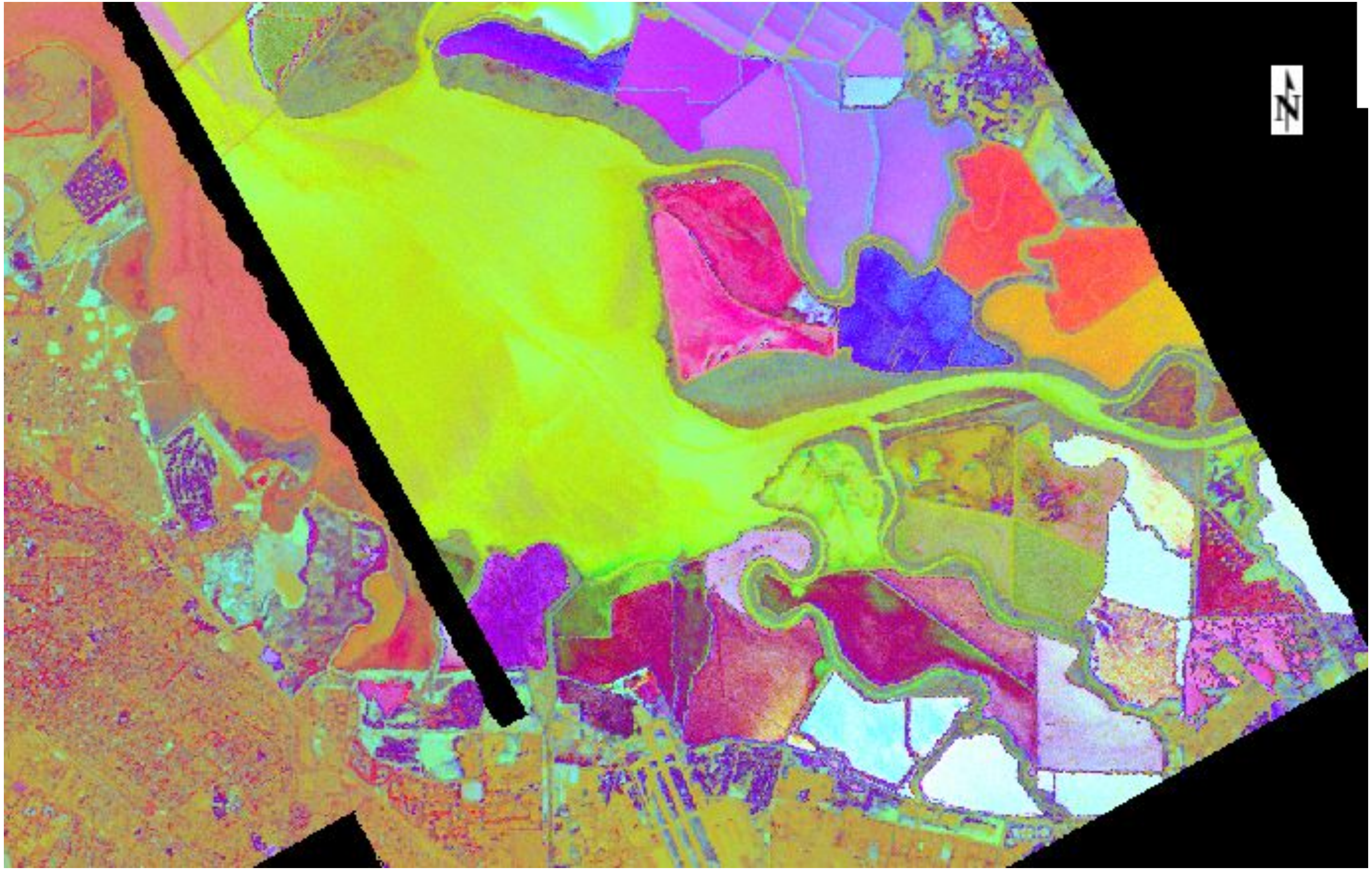


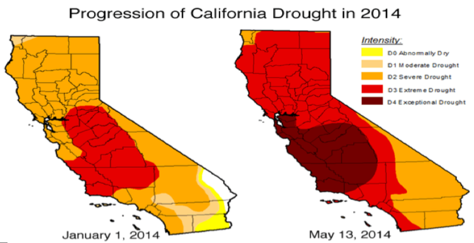
Phytoplankton Food Quality Index

PHYDOTax (PFT algorithm)

- Each PFT assigned a nutritional value
- Values based on evolutionary traits
- Good correspondence between microscopy, HPLC, and PHYDOTax for PFTs

San Francisco Bay Salt Ponds: **2013**





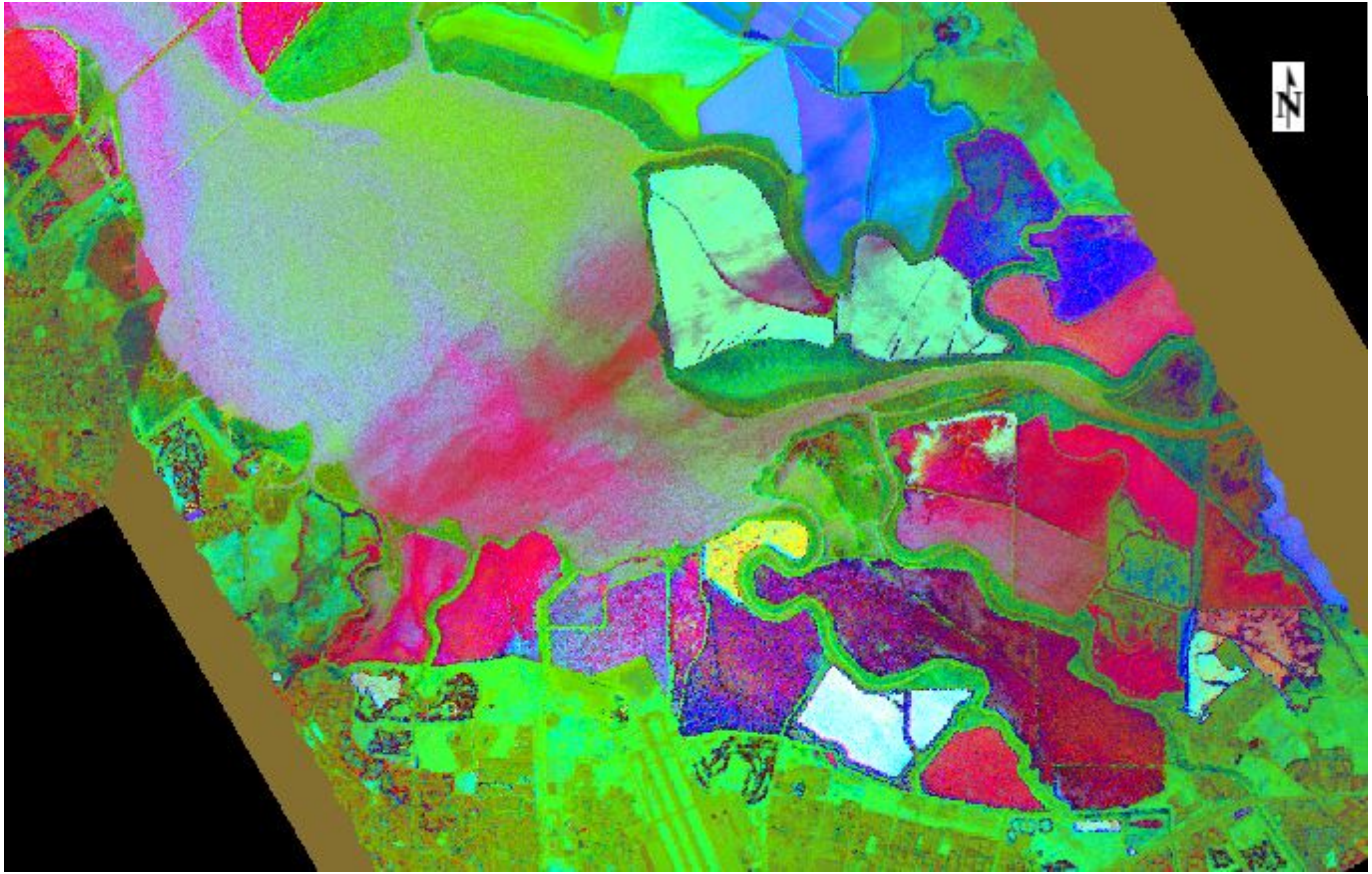
RED: Dinoflagellate

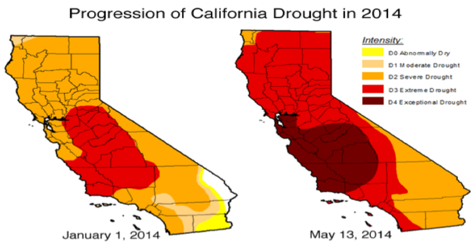
GREEN: Chlorophyte

BLUE: Cyanobacteria

Tyler Dawson
Sherry Palacios
HyspIRI Data

San Francisco Bay Salt Ponds: **2014**





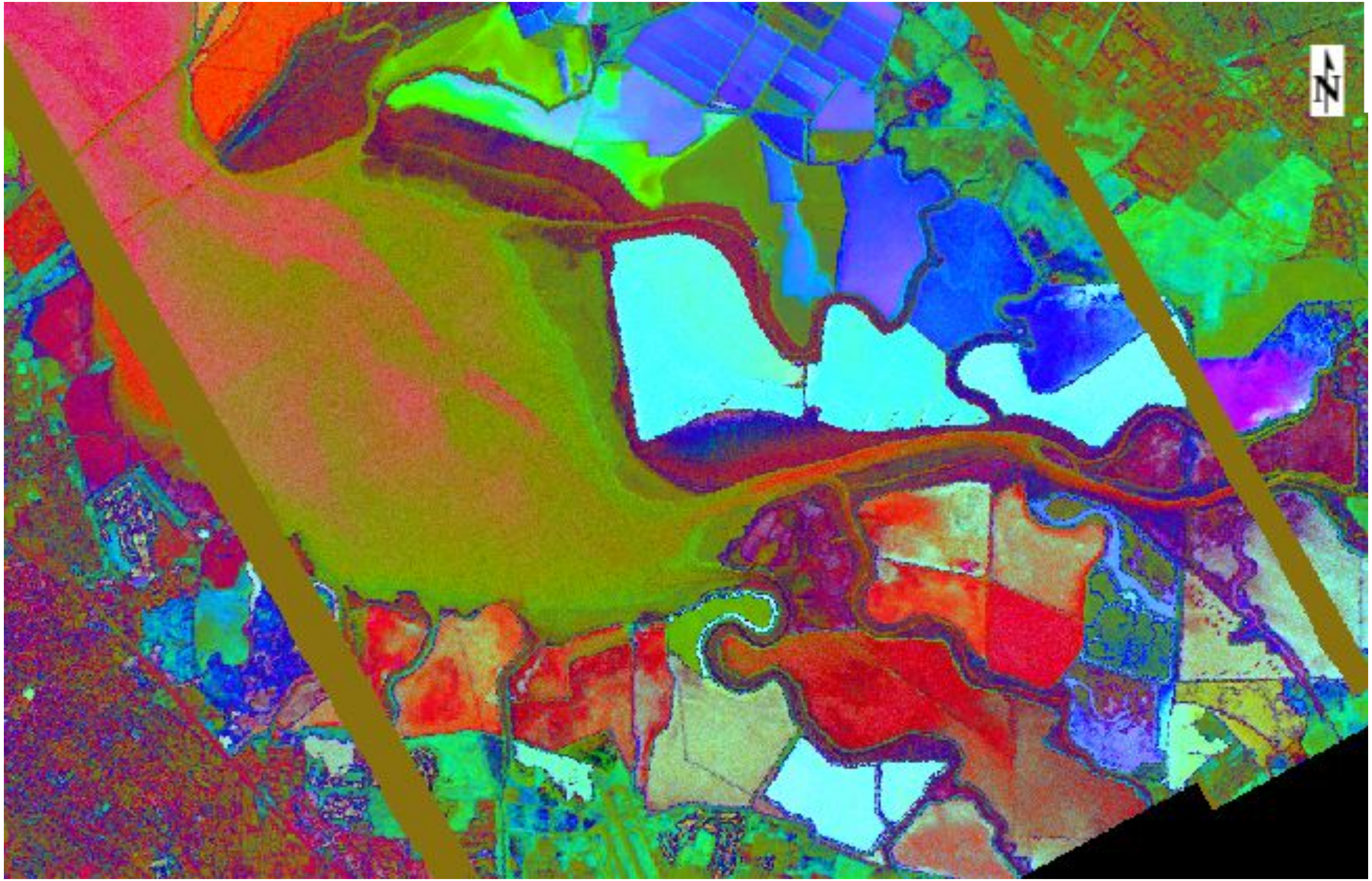
RED: Dinoflagellate

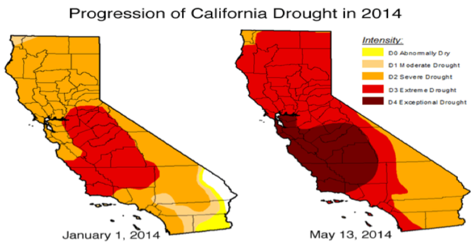
GREEN: Chlorophyte

BLUE: Cyanobacteria

Tyler Dawson
Sherry Palacios
HyspIRI Data

San Francisco Bay Salt Ponds: **2015**





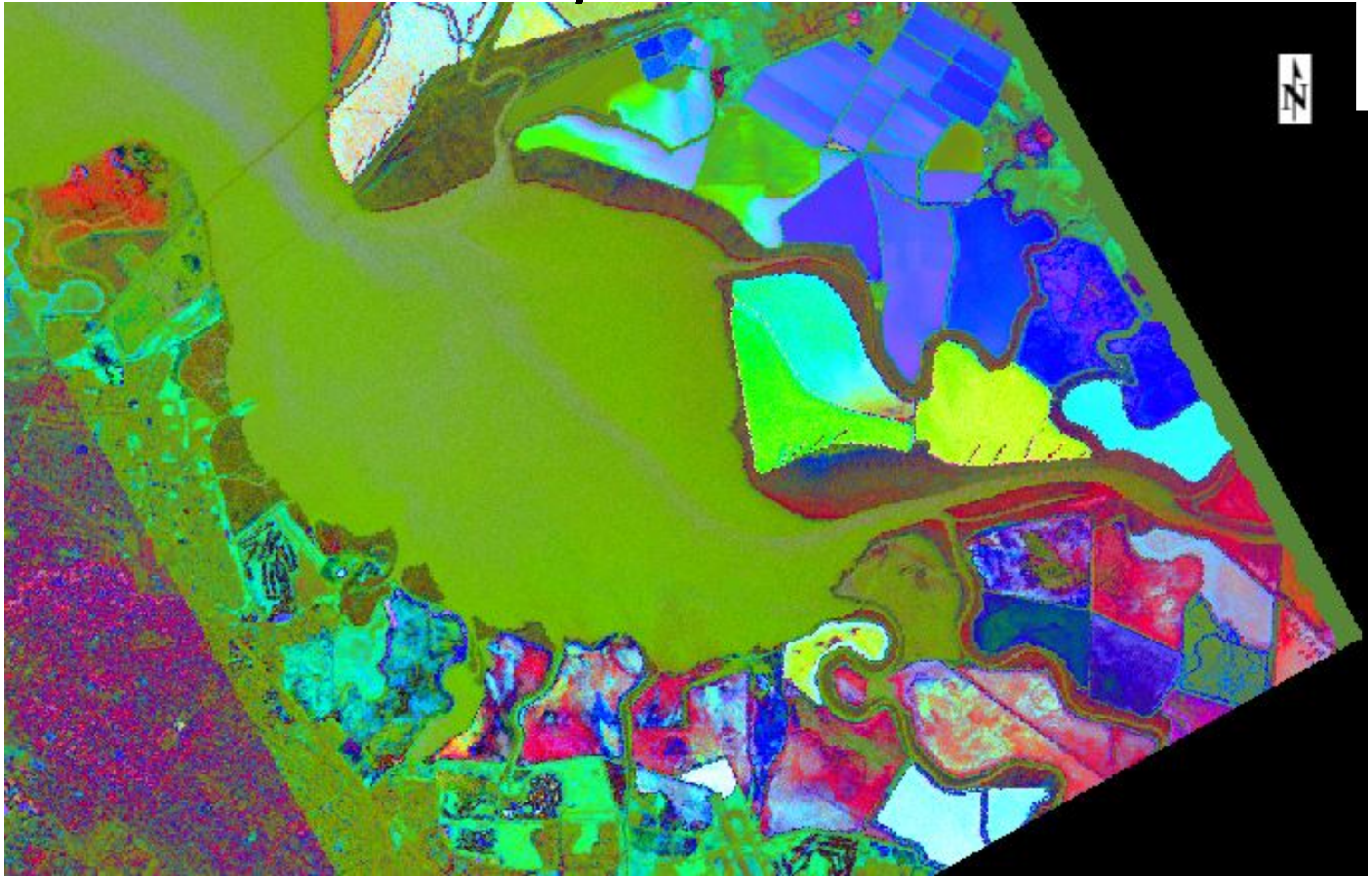
RED: Dinoflagellate

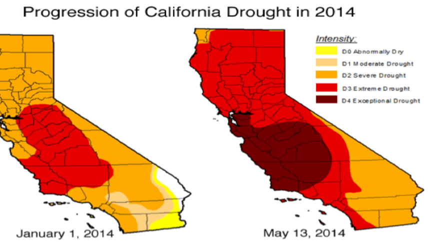
GREEN: Chlorophyte

BLUE: Cyanobacteria

Tyler Dawson
Sherry Palacios
HyspIRI Data

San Francisco Bay Salt Ponds: **2016**





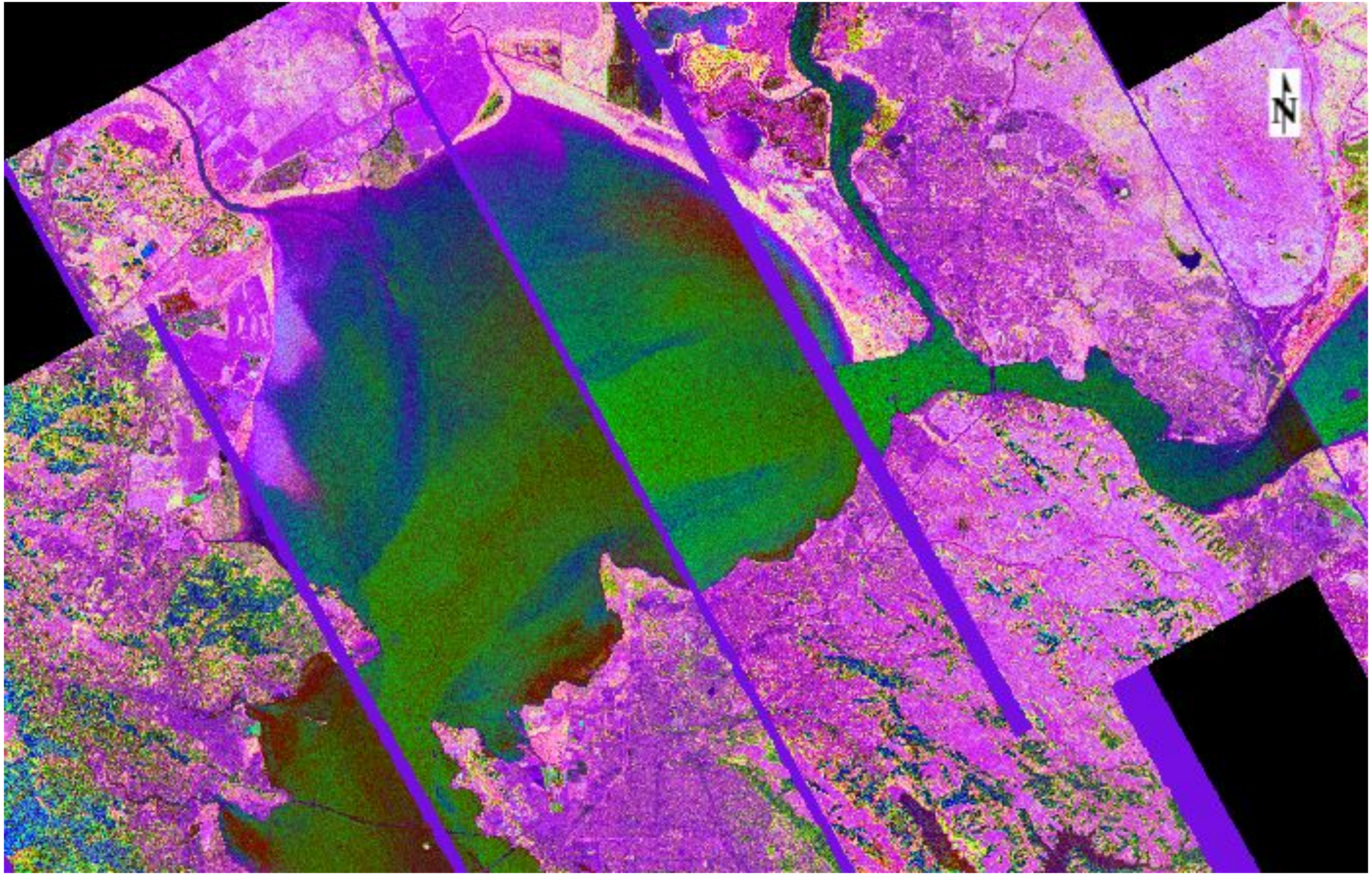
RED: Dinoflagellate

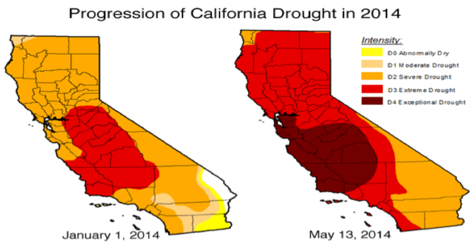
GREEN: Chlorophyte

BLUE: Cyanobacteria

Tyler Dawson
Sherry Palacios
HyspIRI Data

San Pablo Bay, 2015



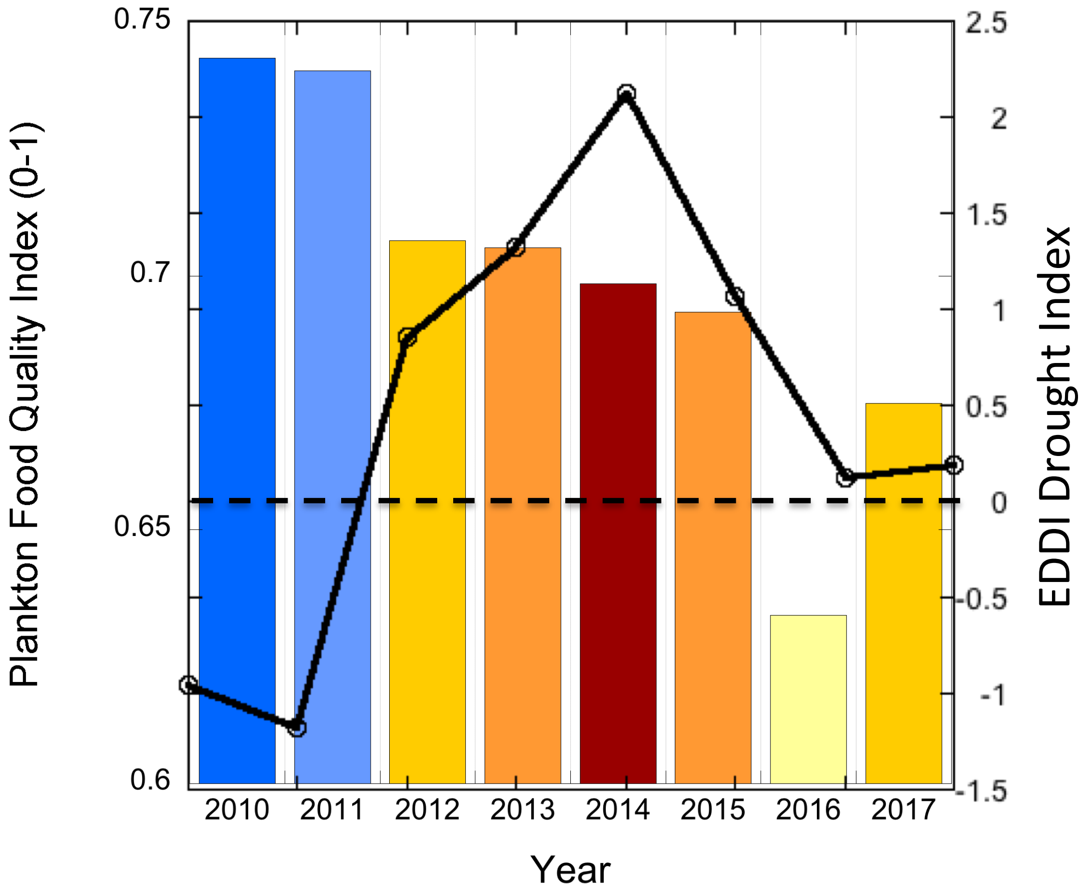


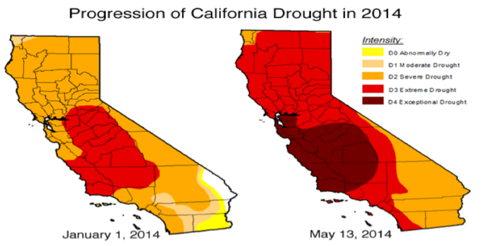
RED: Dinoflagellate

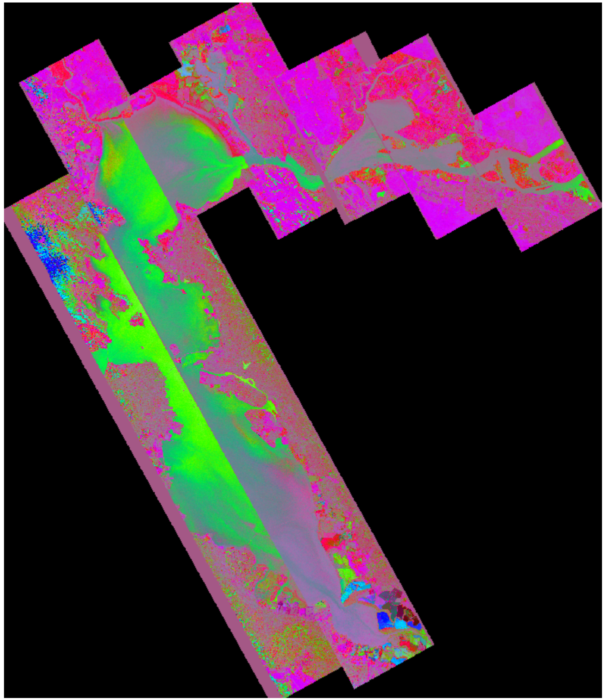
GREEN: Cyanos

BLUE: Chlorophyte

AVIRIS & Microscopy Track the Drought



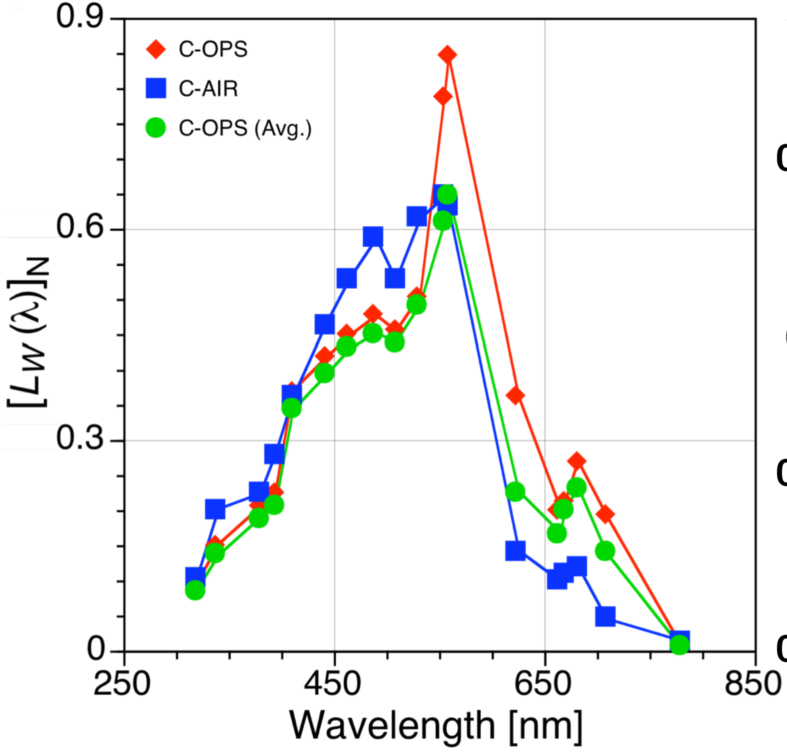




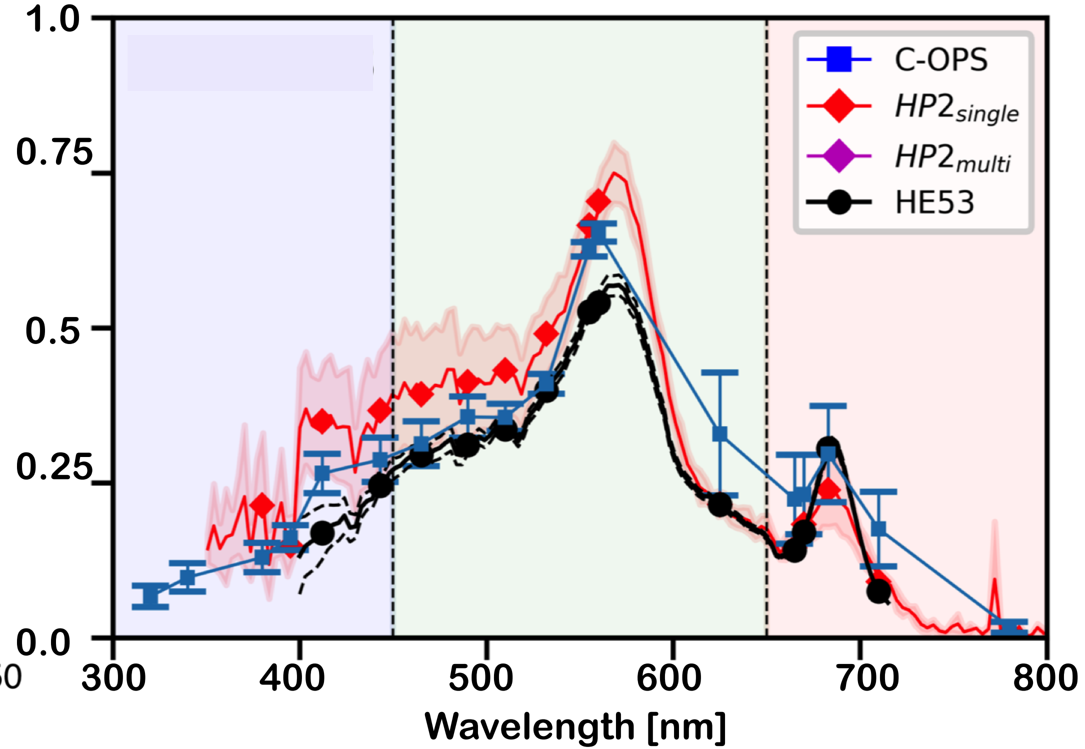
HyspIRI 2016: R=Dinoflagellate, G=Cyano, B=Cryptophyte

Calibration/Validation Requires Measurements at Appropriate Scales!

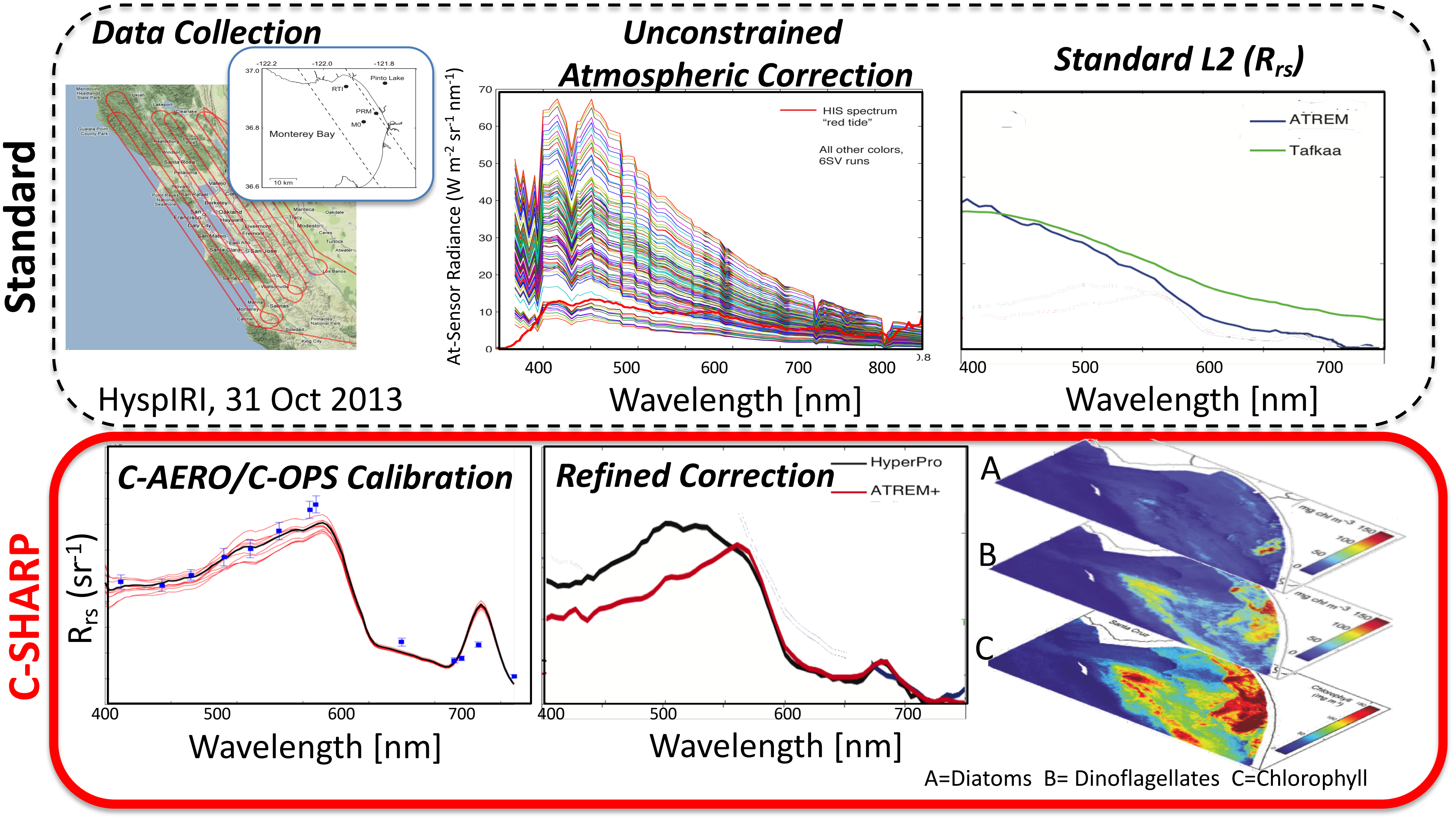
Airborne to In-water Matchup



Multiple In-Water vs. Hydrolight Matchups



Red Tide conditions, Monterey Bay, CA


Standard
Data Collection
-122.2
-122.0
-121.8
37.0
36.8
36.6
Pinto Lake
RTI
PRM
M0
Monterey Bay
10 km
HyspIRI, 31 Oct 2013
Unconstrained
Atmospheric Correction
At-Sensor Radiance (W m^{-2} sr^{-1} nm^{-1})
HIS spectrum
"red tide"
All other colors,
6SV runs
0
10
20
30
40
50
60
70
400
500
600
700
800
Wavelength [nm]
Standard L2 (R_{rs})
ATREM
Tafkaa
400
500
600
700
Wavelength [nm]
C-SHARP
C-AERO/C-OPS Calibration
R_{rs} (sr^{-1})
400
500
600
700
Wavelength [nm]
Refined Correction
HyperPro
ATREM+
400
500
600
700
Wavelength [nm]
A
B
C
mg chl m^{-3}
150
100
50
0
Santa Cruz
Chlorophyll
A=Diatoms B= Dinoflagellates C=Chlorophyll

Algal Biomass is routinely limited to bulk pigments

↓

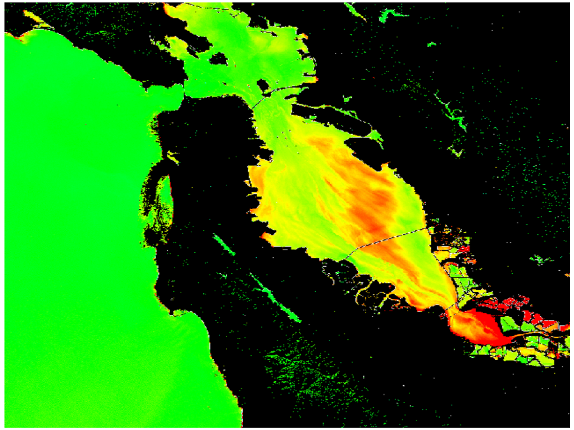
PFTs (PHYDOTax), FQI, Physiology provides more useful information

↓

50m GSD
380-800 nm @10nm
Dedicated Atmos. Corr.
Return rate of ~5-15 d
Robust cal/val program

Science Objectives		Scientific Measurement Requirements	Instrument Functional Requirements	C-SHARP Projected Performance	Logistic/Project Requirements
O1: High-resolution spectra obtained by remote sensing will be used to identify Phytoplankton Functional Types (PFTs), or groups, which allows us to determine food quality. • H1a: Food Quality will increase in San Francisco Bay in response to changes in nutrient load and composition. • H1b: Food Quality will vary in the immediate vicinity of POTW discharge (sources of nutrient pollution). • H1c: PFTs and Food Quality will respond directly to seasonal and interannual forcing, with responses dependent on the specific site and forcing. **O2: High spatial resolution remote sensing data will be used to map the spatial extent and "health" (as chlorophyll:carbon ratio) of bull and giant kelp, the dominant foundation species in Eastern Boundary Currents** • H2a: Kelp canopy area and health are indicative of ecosystem decline (recovery), and more useful than annual aerial maps; these metrics correlate with environmental drivers	Hyperspectral Signals	**Signal:** Multispectral classification analysis discriminates PFT's and kelp species based on water leaving reflectance spectra • Multispectral imagery from aircraft at 20-1000m spatial resolution, bands to match legacy and next generation orbital sensors • Total sea surface radiance (L_t) and nadir sea surface radiance (L_n) at aircraft, bands to match legacy and next generation orbital sensors, high dynamic range	**Imaging spectrometer:** 380-800nm at 10 nm resolution, Signal to Noise Ratio (SNR) 200:1 at 400 nm, typical offshore ocean water target, 30-60° Field of View (FOV), 50m ground sampling resolution (GSR)	**PRISM Imaging Spectrometer:** 350-1050nm @ 3.5nm FWHM, FOV: 30.7°, SNR: 500:1 for single integration, SNR: 2000:1 @ 450nm with multiple integrations, GSR: 3m@ 3658m MSL, <1% polarization sensitivity (demonstrated in Monterey 2012)	**General** • Mesoscale satellite retrievals from existing/planned satellites • Time-series from existing observation systems **Field Deployments** • ≤14-day deployments, 2-3 seasons, at least 2 years • Research vessel(s) with berthing and sea worthiness for offshore sampling; sea state <5, <3 preferred • Autonomous vehicle deployment at targeted sites for far-field end-members • Airborne transects including (1) long-range (10s km) surface mapping; (2) low- (LSA) and high-altitude profiles for atmospheric correction • Fixed location sun photometry • Sample multiple targets within a flight window **Airborne Requirements** • Clear skies (<25% cloud cover) • Synchronized data acquisition: imaging spectrometer, radiometers, sun photometry, ancillary data • Sun elevation 25-50° (spectrometer) and 25-65° (radiometers) • Flight lines @ LSA and 10,000' • Coordination with satellite overpasses and in situ observations **Sampling Requirements** • In situ sampling of relevant optical, biogeochemical parameters • In situ sampling of IOPs, AOPs, biogeochemical data ±30 minutes of airborne imaging • In situ sampling of kelp CHL:C for each site **Synthesis** • Data/models to characterize key physical and biogeochemical properties at seasonal and interannual time scales • Central data archive; transfer to relevant repositories (OB.DAAC) • Extrapolation from C-SHARP to other airborne/satellite platforms • Publication/documentation of results
	Atmospheric Noise Removal	**Noise:** Significant correction required for atm., ocean surface, and water column scattering/ absorb • Atmospheric measurements coincident with airborne data for atmospheric correction (aerosol optical depth, column water vapor, total column ozone, aerosol size spectra)	**Airborne Sun-Sky Spectrometer:** 380-1640nm range at 10 nm resolution (aerosols), 3 nm (gasses), SNR 10^5, <3° FOV, with hemispherical sun tracking and sky scanning	**4STAR Tracking Sun/Sky Spectrometer:** 350-1700nm @2-10 nm FWHM, 1.3-2° FOV, 10^5 dynamic range, <2% radiometric uncertainty (demonstrated in SEA4CRS) **C-OSPREy Field Sky-Scanning Radiometer:** same as C-AIR except 305-1640nm, 3-axis polarizer, sun tracking, thermally stabilized; microradiometers match C-AIR/C-AERO	
	High Dynamic Range Spectral Data	**Signal:** Very high dynamic range and linearity required to retrieve signal from noise • Solar irradiance (E_s) at aircraft, bands to match legacy and next generation orbital sensors, high dynamic range • Sky radiance (L_i) at aircraft, bands to match legacy and next generation orbital sensors	**Precision Bandpass Radiometers:** match key legacy, existing, and planned ocean color instrument bands, 10 nm resolution, SNR, ≥1000:1, ~2-3° FOV, capable of operating at Lowest Safe Altitude, 10 Hz minimum achieve 50m GSR E_s, L_i, L_t and L_n	**C-AIR:** 320-1020nm @10nm FWHM with 1245nm @15 nm,1640nm @ 30nm, Dynamic Range 10^{10}, FOV: 2.5°, Uncertainty ≤3.5%, sampling @ 15 Hz (demonstrated in COAST,OCEANIA, C-HARRIER); L_n **C-AERO:** same as C-AIR but with stray light shroud; thermal stabilization; sampling @ 25 Hz (demonstrated in C-HARRIER); E_s, L_i, L_t	
	In-Water Validation	• In-water measurements of pigments, phytoplankton, & water-leaving radiances • In-water measurements of inherent optical properties (IOPs; absorption; scattering; backscatter ratio) to model remote sensing reflectance, with <25% variance between modeled and measured values • In-water measurements of apparent optical properties (AOPs; downward irradiance; upwelling radiance) at 10 cm (highly turbid/productive water) to 1 m vertical resolution (homogenous water column, coastal to offshore) from 380-800 nm	**In-water bandpass radiometers:** in-water measurements to constrain atmospheric correction and imaging spectrometer • In-water measurement of 6 PFTs by microscopy or pigment analysis, to within 20% error • Standard optical and water sampling at reference stations	**C-OPS w/C-PrOPS:** same as C-AIR except 313-875nm and FOV: 6.4° , 10cm vertical resolution (demonstrated in COAST, OCEANIA, C-HARRIER, MODIS, ACE, & GEO-CAPE) **C-PHIRE (delpoyed from SV3):** same as C-AIR except 305-900 nm, <1-10 nm, 10^5-10^{10} dynamic range, FOV 6.7° **WETLabs/HOBILabs IOP Package**: 400-750 nm, <10% error in modeled water leaving radiance (using Hydrolight) compared to C-OPS (demonstrated in HyspIRI, C-HARRIER)	
	Spatial/Temporal Distribution	**Experimental Design** • Study sites encompass critical environmental gradients in nutrients, water quality, and physical forcing (e.g. upwelling, salinity, temperature, particle load, water clarity) • Extrapolation in space/time from validation sites to region using in-water, airborne, and satellite observations, and modeled spectra • All measurements at local/regional, & multi-year event/ seasonal/ inter-annual scales	**Functional Requirements** • Airborne observations at Lowest Safe Altitude (LSA) with matching in-water measurements for calibration/validation and atmospheric correction • Field/airborne transects along axis of variability with a spatial scale of ~750 km: inland/onshore/ offshore, latitudinal, seasonal		

Thank You



Collaborators:

- David Thompson, Rob Green & Ian McCubbin, JPL
- Bo Cai Gao, NRL
- Stan Hooker, GSFC
- John Morrow, Biospherical Instruments
- Misty Peacock, Jim Cloern, Dave Senn (NWIC, USGS, SFEI)
- The HyspIRI, MASTER, and AVIRIS teams

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- \- NASA HyspIRI Project (Woody Turner)
- \- NASA HQ20 Project (Paula Bontempi)
- \- NASA Student Airborne Research Program (Barry Lefer)
- \- NASA C-HARRIER project (Paula Bontempi, Barry Lefer)