Observing Coastal and Inland Aquatic Ecosystems from Space

Kevin R. Turpie
UMBC, JCET / NASA, GSFC

Frank Muller-Karger
University of South Florida

HyspIRI Science Workshop
Cal Tech Pasadena, California USA
19 October 2016

Decadal Survey Reports

NEW NEED TO UNDERSTAND CHANGING COASTAL AND INLAND AQUATIC ECOSYSTEM SERVICES

Kevin Turpie, David W. Allen, Steven Ackelson, Thomas Bell, Heidi Dierssen, Kyle Cavanaugh, Joshua B. Fisher, James Goodman, Liane Guild, Eric Hochberg, Victor V. Klemas, Samantha Lavender, Christine Lee, Tiffany Moisan, Frank Muller-Karger, Joseph Ortiz, Sherry Palacios, David R. Thompson, Richard Zimmerman

GLOBAL OBSERVATIONS OF COASTAL AND INLAND AQUATIC HABITATS

Kevin Turpie, Steven Ackelson, Thomas Bell, Heidi Dierssen, James Goodman, Robert Green, Liane Guild, Eric Hochberg, Victor V. Klemas, Samantha Lavender, Christine Lee, Peter Minnett, Tiffany Moisan, Frank Muller-Karger, Joseph Ortiz, Sherry Palacios, David R. Thompson, Richard Zimmerman

MONITORING COASTAL AND WETLAND BIODIVERSITY FROM SPACE

Frank E. Muller-Karger, Erin Hestir, Kevin Turpie, Dar Roberts, David Humm, Steve Ostermann, Noam Izenberg, Mary Keller, Frank Morgan, Robert Frouin, Arnold Dekker, Royal Gardner, James Goodman, Blake Schaeffer, Brian Franz, Heidi Dierssen, Ray Najjar, Natassa Romanou, Maria Tzortziou





Aquatic ecosystems: Services where land, ice, and water meet.

Ecosystem services:

- Support among the most biologically diverse places on Earth.
- Buffer human and animal habitats against storms and floods.
- Provide erosion control; can build or preserve land.
- Support fisheries that provide food, livelihood, and recreation to roughly half of the global population (Barbier et al 2011).
- Have cultural and recreation value.
- Per unit area, amongst the most productive places on Earth.
- Play a key role in the cycling of carbon, minerals and nutrients.
- Inland waters provide critical freshwater resources for human consumption, irrigation, sanitation, industry, recreation, and play a vital role in human health and safety.
- **Support industry worth hundreds of billions of USD.**
- **Support hundreds of thousands of jobs in the USA.**
- **Coasts provide over $56 trillion in benefits**

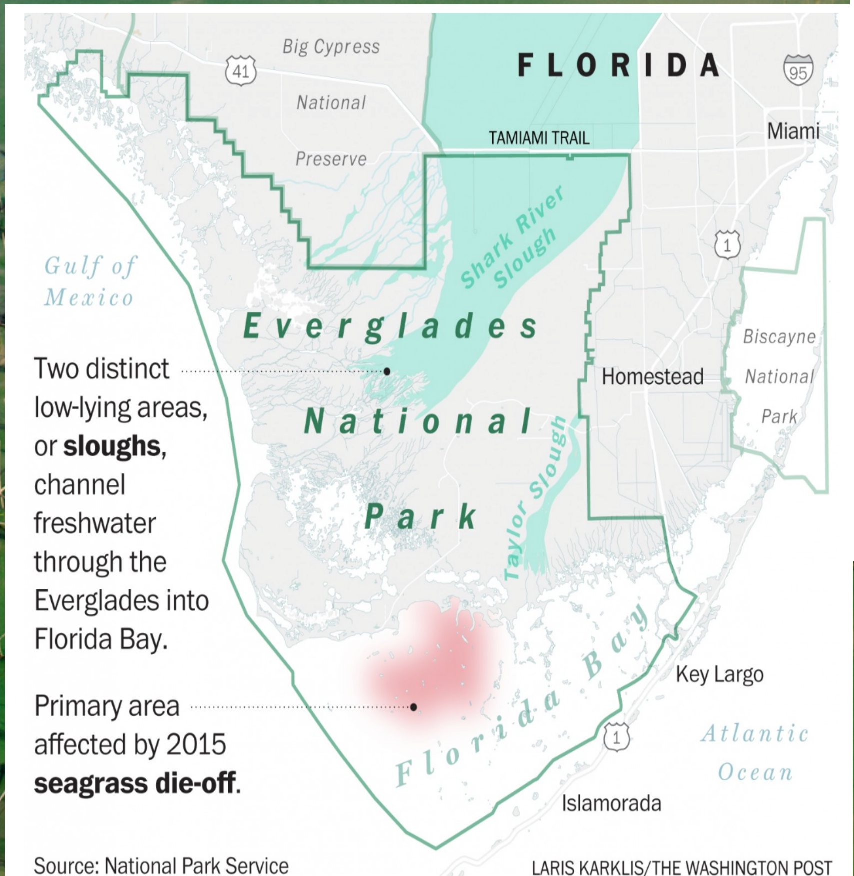
These are also some of the most endangered ecosystems in the world

Coastal ecosystems, from high latitudes to the tropics are undergoing massive change NOW.

- **Sea Grasses** losses have risen to 7% yr^{-1} since 1990 (Waycott et al., 2009), having major impact on coastal productivity, biodiversity, and fisheries.
- Globally, **wetland habitats** have declined 64–71% and the degradation rate continues to increase due to climate change, sea level rise, and human encroachment. (Davidson et al., 2014).
- Many **coral reef** systems are currently in decline due to direct human impacts and changing ocean conditions linked to climate change, e.g., mechanical erosion by storms, elevated water temperature, and acidification (Hughes et al., 2003).
- **HAB events** are being introduced through human activities or being driven by climatic change (Anderson et al., 2002).
- **Invasive species** are influenced by climate change (Guareschi et al., 2013) can have profound impact on ecosystem function (Rahel and Olden, 2008).

Over 70% of humanity faces ***high*** risk of losing benefits from coasts by 2025

NATIONAL GEOGRAPHIC



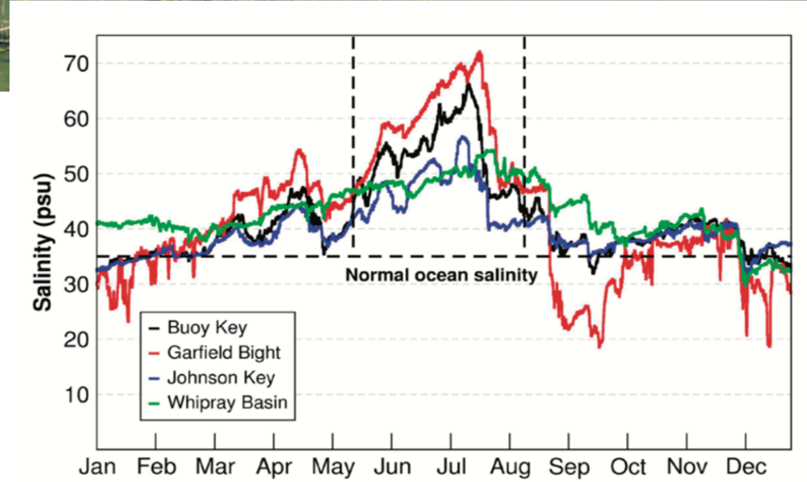


Figure 3. Daily averages of continuous readings of Florida Bay salinity at Garfield Bight (red), Whipray Basin (green), Johnson Key (blue), and Buoy Key (black) monitoring stations during 2015. Ocean water averages 35-37 psu.

2015 Florida Bay Seagrass Die-Off

National Park Service, U.S. Department of the Interior
South Florida Natural Resources Center Everglades National Park
May 2016

- 40,000 Acre Die-Off of Sea Grass.
- 2nd major seagrass die off in three decades.
- Die-off was more rapidly than 1987-90.
- Tied to drought and poor water management.
- Threatens a $1.2 billion sport fishing industry.

This massive seagrass die-off is the latest sign we're failing to protect the Everglades
Washington Post, Chris Mooney, April 27 2016

NATIONAL GEOGRAPHIC

Figure 7. The die-off produced mats of floating seagrass on the surface of the water and plant litter decaying on the bay bottom. Bacterial decomposition of large amounts of organic matter can lead to anoxia and algal blooms.

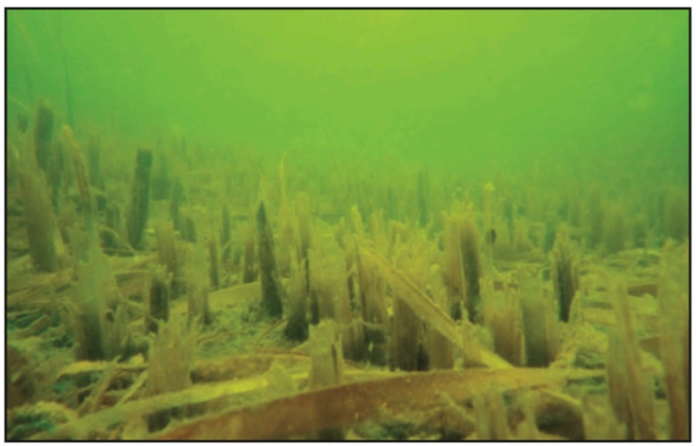


Figure 8. Many areas of former beds of seagrass have been denuded. Only stubble of the turtle grass remains.

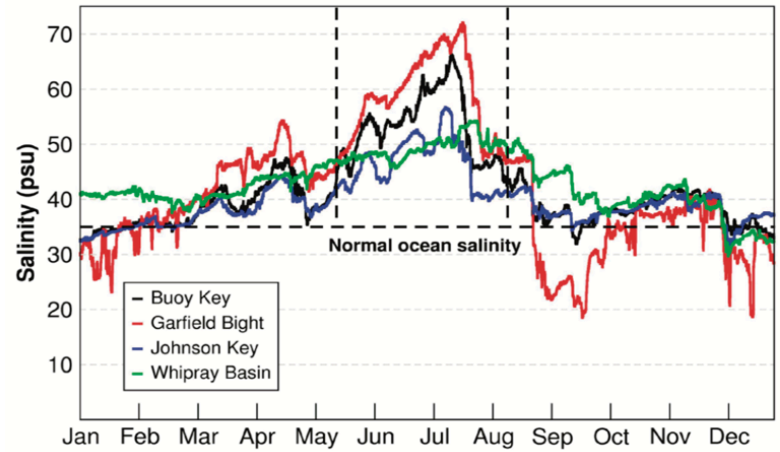


Figure 3. Daily averages of continuous readings of Florida Bay salinity at Garfield Bight (red), Whipray Basin (green), Johnson Key (blue), and Buoy Key (black) monitoring stations during 2015. Ocean water averages 35-37 psu.

2015 Florida Bay Seagrass Die-Off
National Park Service, U.S. Department of the Interior
South Florida Natural Resources Center Everglades National Park
May 2016

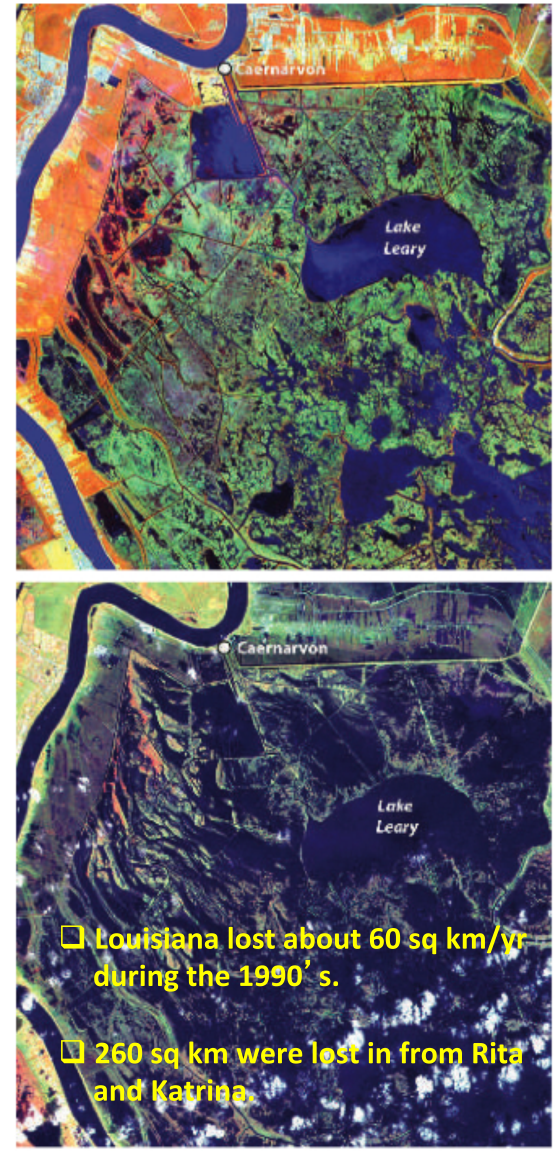
- 40,000 Acre Die-Off of Sea Grass.
- 2nd major seagrass die off in three decades.
- Die-off was more rapidly than 1987-90.
- Tied to drought and poor water management.
- Threatens a $1.2 billion sport fishing industry.

This massive seagrass die-off is the latest sign we're failing to protect the Everglades
Washington Post, Chris Mooney, April 27 2016

THREATS TO COASTAL WETLANDS

- Most of the world’s population share watersheds with wetlands, depend on their services, but likewise threaten these resources, directly or indirectly.
- Wetlands are highly vulnerable to human activities, exploitation, and climate change.
- Nearly 1/2 of all American wetlands lost since colonial times.

From Uncertain Threats to Saltmarshes of the Delaware Inland Bays
Chris Bason, Delaware Center for the Inland Bays (2006)



- Louisiana lost about 60 sq km/yr during the 1990’s.
- 260 sq km were lost in from Rita and Katrina.

Before and after: satellite images show marshland lost in Breton Sound, Louisiana, one of the areas hit hardest by Hurricane Katrina.

Marris, E. (2005). The vanishing coast, *Science*, 438, pp 908-909.

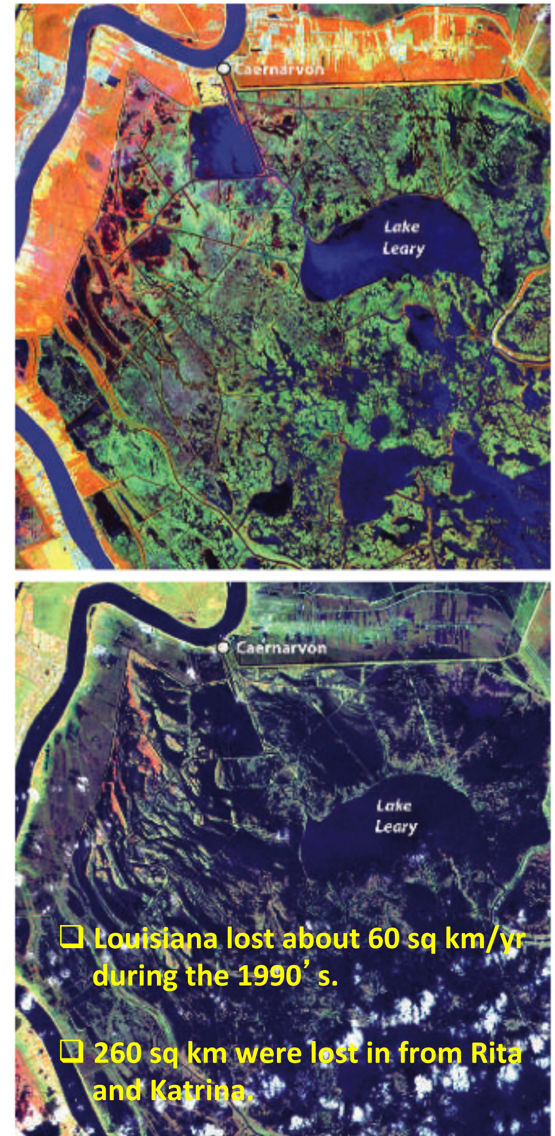
THREATS TO COASTAL WETLANDS

- Legislation in the 1970's has mitigated most of the direct distruction of American wetlands.

- Nonetheless, a new inter-agency task force was established this year to address reports of higher than expected wetland loss in the USA.

- Wetlands are still at risk in other regions of the globe and other threat processes exist.

From Uncertain Threats to Saltmarshes of the Delaware Inland Bays
Chris Bason, Delaware Center for the Inland Bays (2006)



Before and after: satellite images show marshland lost in Breton Sound, Louisiana, one of the areas hit hardest by Hurricane Katrina.

Marris, E. (2005). The vanishing coast, *Science*, 438, pp 908-909.

Objective: Develop knowledge to promote well-planned, healthy and resilient coastal communities globally.

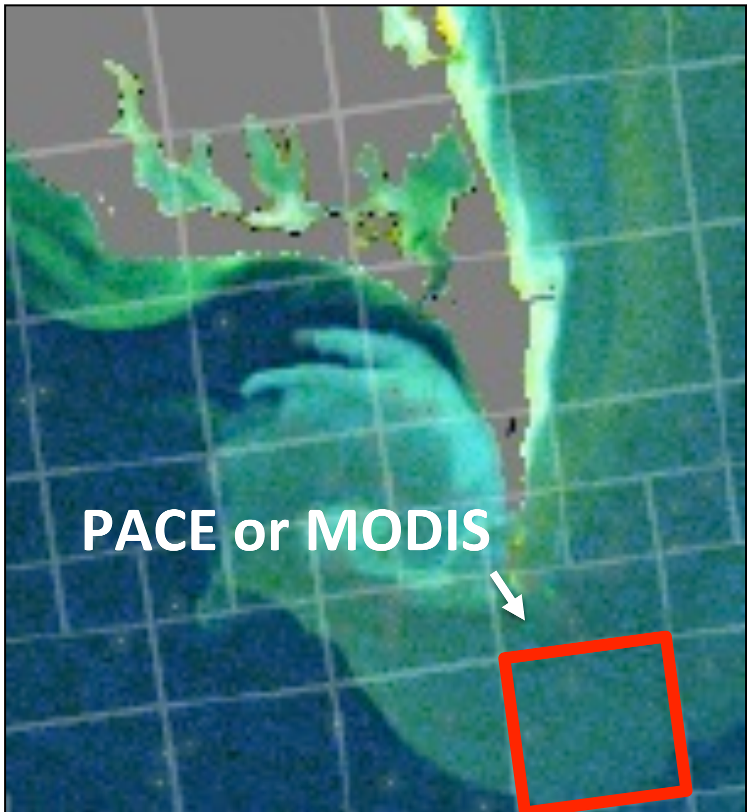
…This requires space-based observation technologies

Coastal and inland aquatic science

Questions:

- What are the distribution, abundance, function, and state of coastal and inland aquatic ecosystems on regional and global scales? At what rate are these quantities changing?
- What are the material fluxes across the boundaries between land, water, and air; how are they changing?
- What are the linkages of these changes to climate, human activities or natural processes?
- How are these changes interconnected and what are the consequences to important ecological services, e.g., fish stocks and water quality and availability?

Issue: spatial resolution



1 km pixel grid on 30 m Landsat-8 OLI image

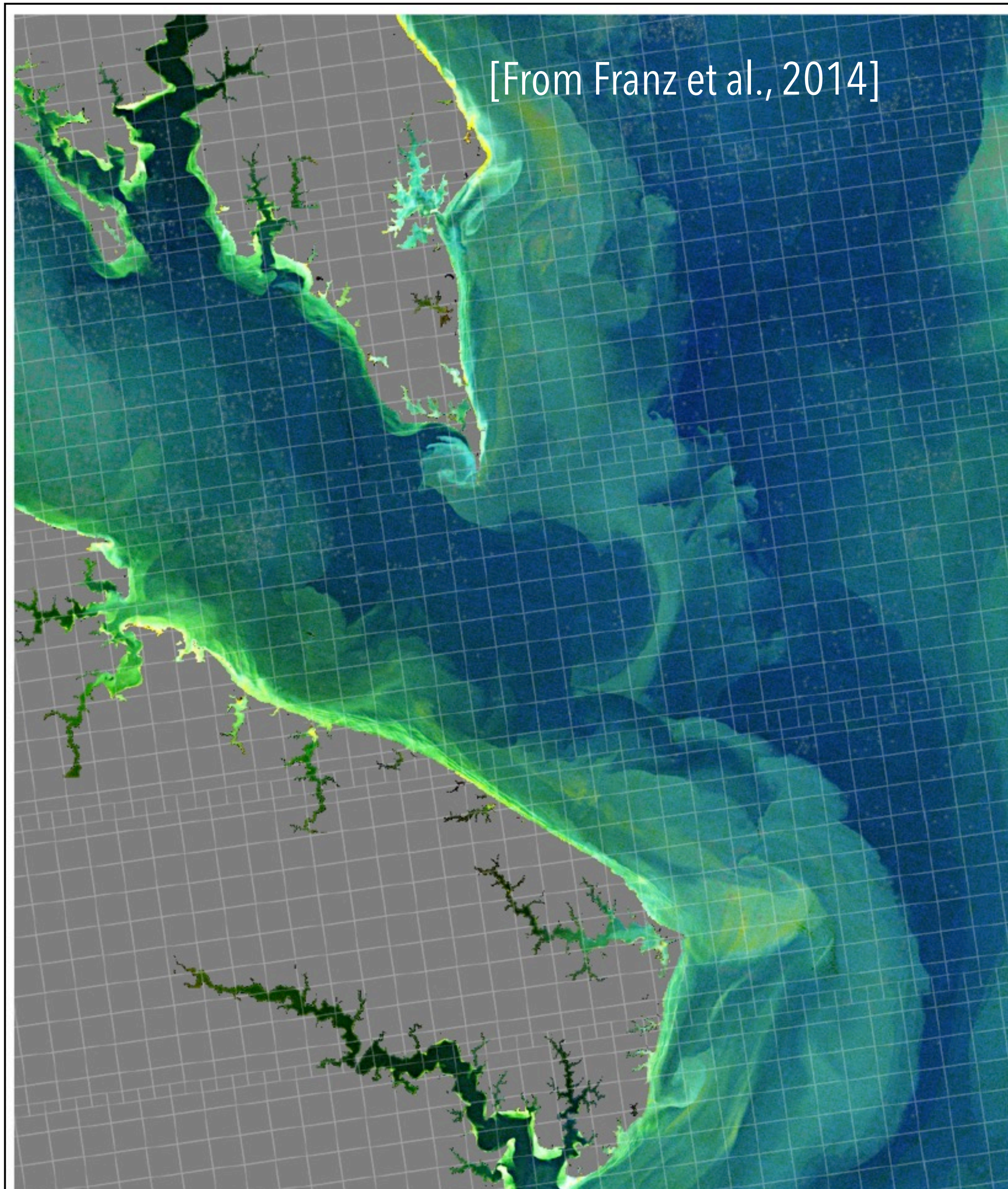


Figure 5: *Three-band water-leaving reflectance composite image from OLI at the location where the Potomac River enters Chesapeake Bay. MODIS Aqua scan pixel boundaries for the same date are overlaid to demonstrate the sub-pixel variability revealed by the higher spatial resolution of OLI. The Rrs(λ)were retrieved using standard NASA ocean color processing in SeaDAS, and red, green, and blue reflectances at λ=(655, 561, 443nm) were combined to form the image.*

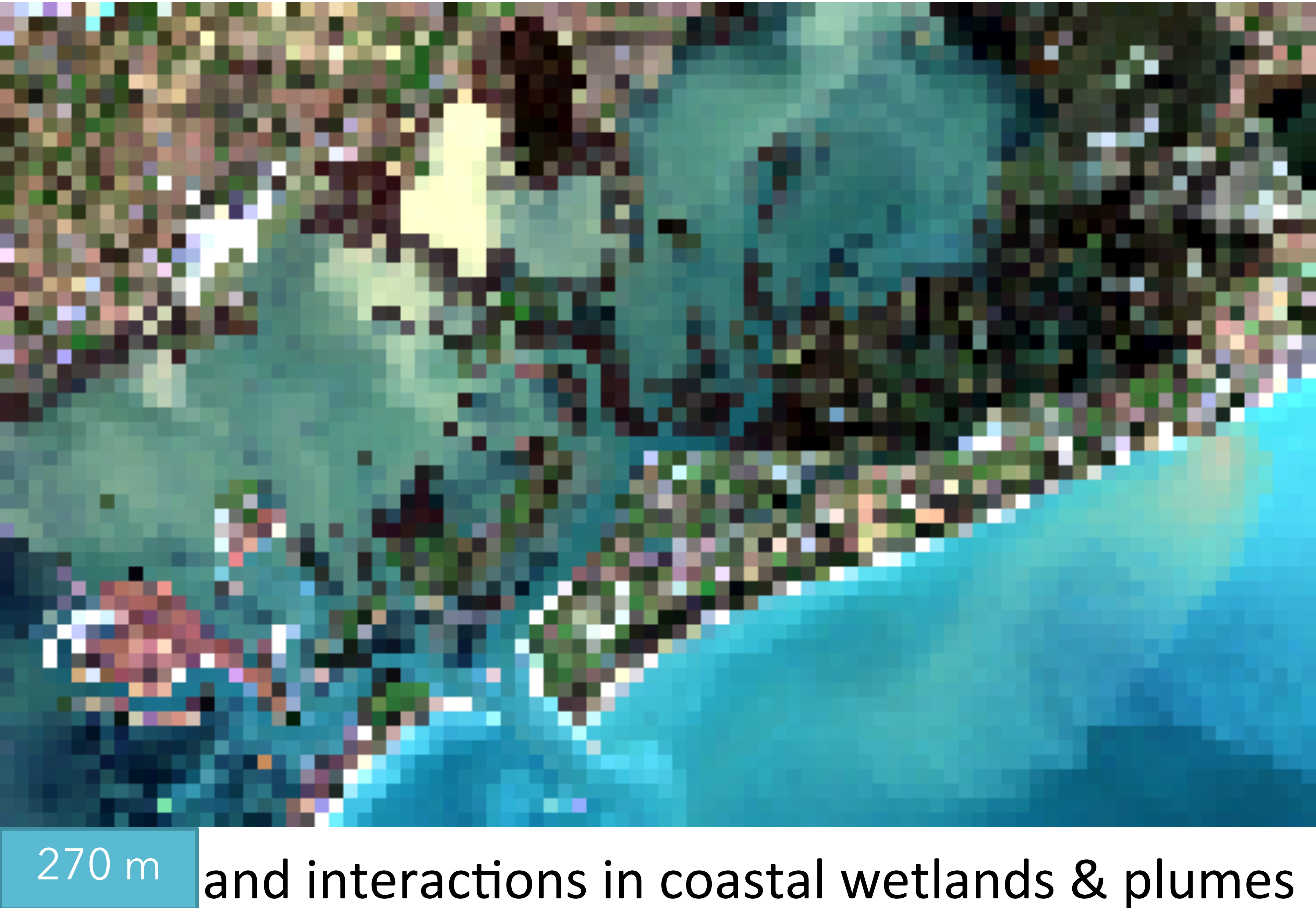
30 m

Landsat 8 scene: Venice lagoon, Italy

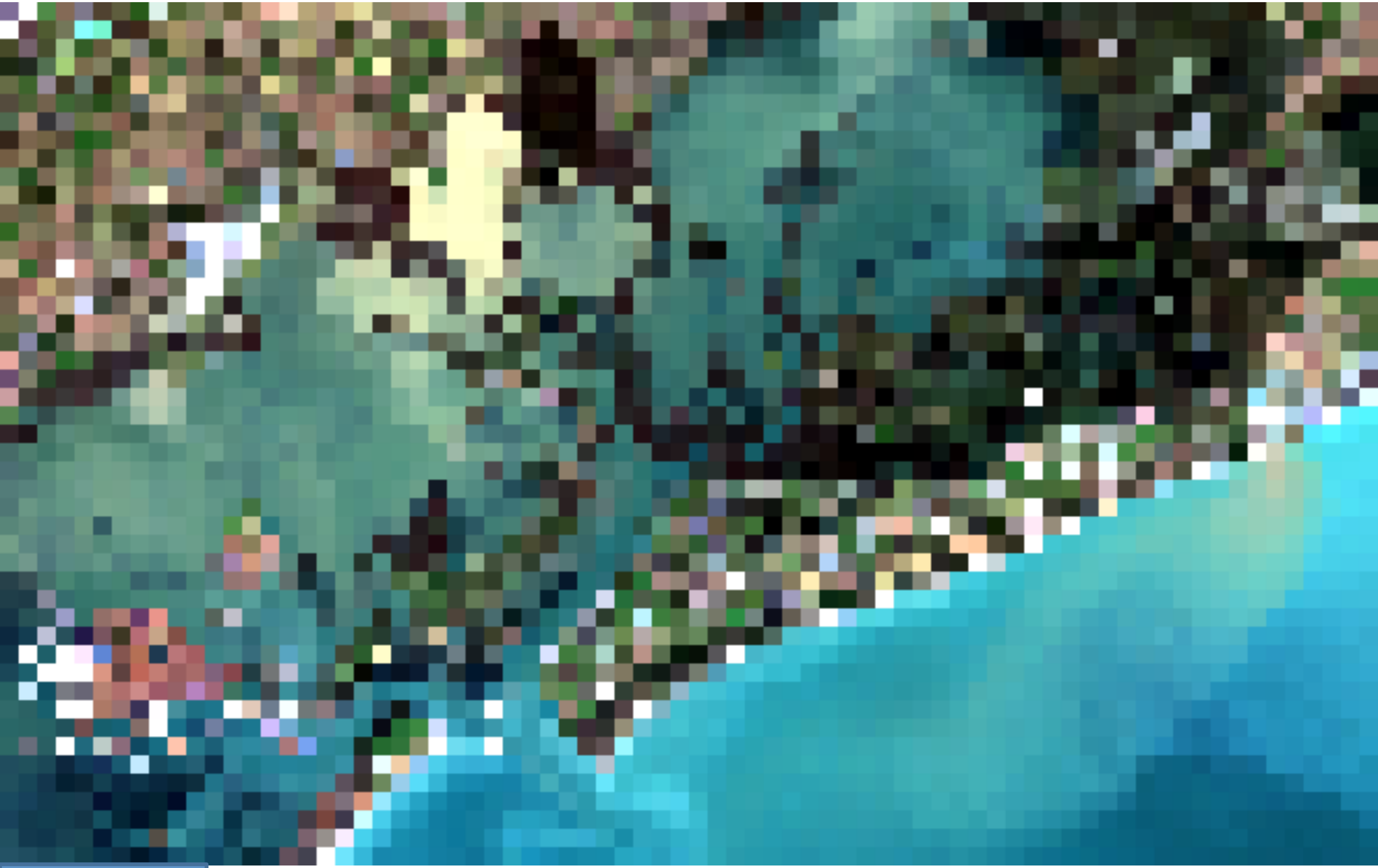
Binning improves SNR

150 m

But we lose detail about sediment, CDOM,



and interactions in coastal wetlands & plumes



330 m

High spectral resolution helps differentiate organisms because they show different phenology

Winter: species hard to separate

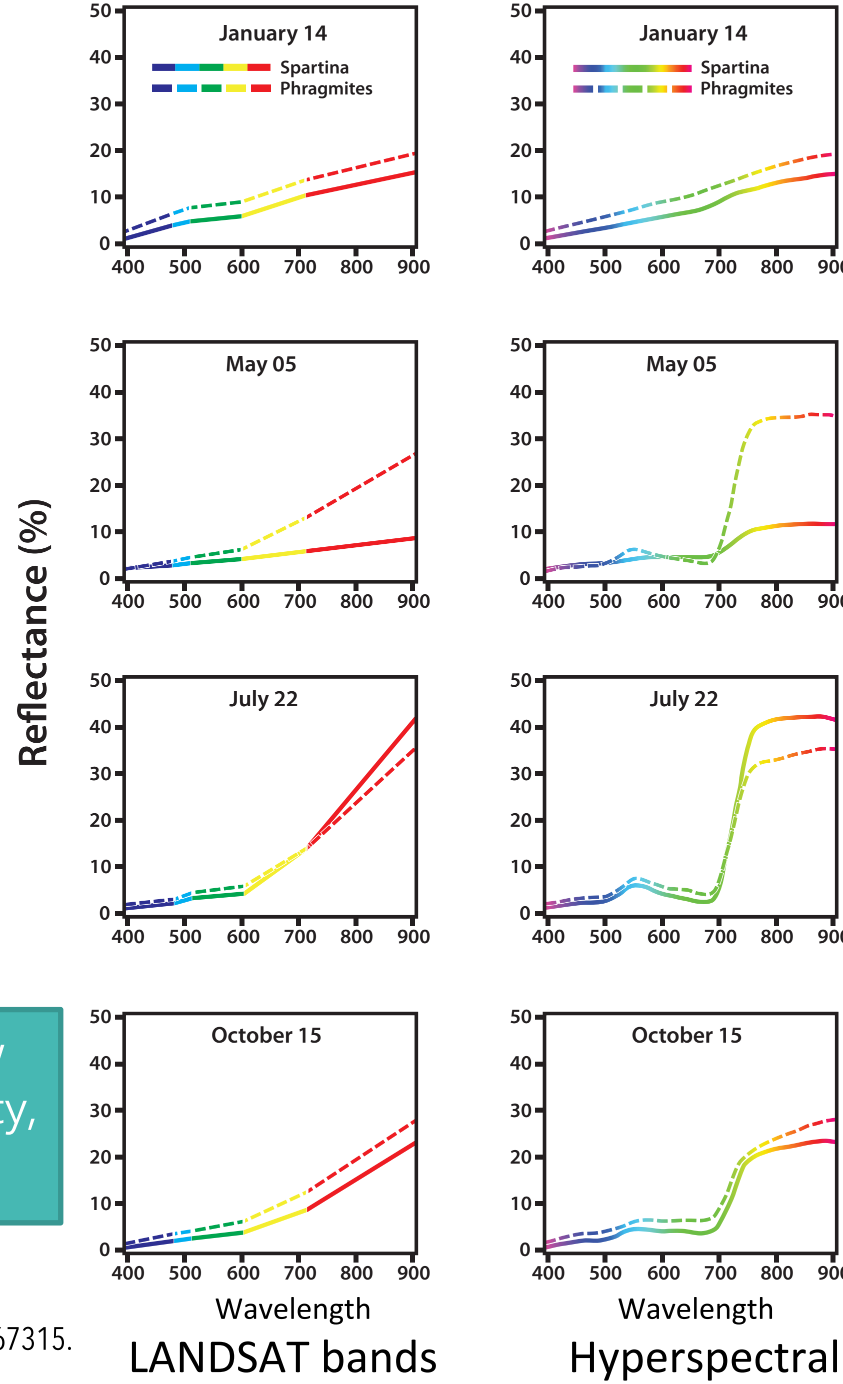
↓

Spring: species easier to separate

↓

Summer: further differentiation

Relative changes allow evaluation of biodiversity, invasive species, etc.



From: Ouyang Z-T, et al. 2013. Spectral Discrimination of the Invasive Plant Spartina alterniflora at Multiple Phenological Stages in a Saltmarsh Wetland. PLoS ONE 8(6): e67315. doi:10.1371/journal.pone.0067315)

Issues: detecting temporal change

- A global mapping mission with 30m resolution and 16-day revisit period can detect secular changes at pixel scales over a mission duration of three or more years.

- This includes long-term response to disturbances, climate change, human activities, and other drivers of change.

Issues: detecting temporal change

Passive RS – classification, composition, condition.

- **Multi-band Optical –** discrimination of cover type; may require higher spatial resolution.
- **Hyperspectral Optical –** improved discrimination, possibly better detection of change at subpixel scales; better observations of fluorescence.
- **Thermal –** would provide additional wetland and watershed conditions (e.g., soil moisture).

Active RS – (SAR and LIDAR) provide vegetation structure (e.g., Sentinel 1); LIDAR can provide water column optical constituents.

Issues: detecting temporal change

- High temporal resolution is required to see changes in phenology, another key indicator of response to environmental changes. (e.g., sampling every couple of days, depending targeted phase of growth cycle)

- Very high temporal sampling (hourly sampling) is required to characterize and monitor changes in response to tidal and diel cycles and immediate response to distrubances. (e.g., GeoCAPE).

Coastal and inland aquatic observation strategies

High spatial resolution ≤30 m for foundational species, rivers and small water bodies; ≤100 m for open water phytoplankton.

High-performance radiometry

- High SNR, large radiometry range and resolution, minimal polarization sensitivity, minimal cross-talk or other out-of band, atmospheric correction scheme (including adjacency), sun-glint avoidance, cloud screening/masking, etc.

Highly accurate geolocation and band-to-band registration

Obs Strategy 1 - Foundational species areal extent and secular change (e.g., HyspIRI)

- Low temporal
- High spectral (VIS, SWIR and TIR)

Obs Strategy 2 - Phenology characterization and change (see next slide)

- High temporal (<2 days)
- High spectral (VIS, SWIR)

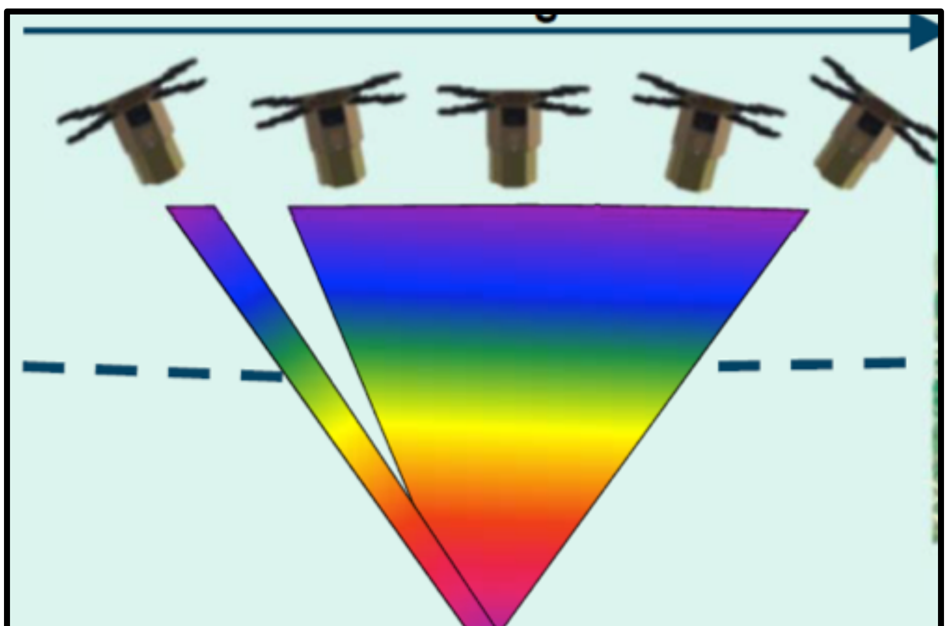
Obs Strategy 3 - Tidal and diel processes (GeoCAPE?)

- Very-high temporal (hourly)
- High spectral (VIS, SWIR and TIR)

Possible observation technique :

(Technology Readiness Level: TRL >6-7, now!)

- -Hyperspectral 30 m spatial resolution sensor
- -Sample several hundred 30x30 km areas every 3 days
- -3-day exact repeat orbit
- -1 ‘slow’ and 1 ‘fast’ scan of same target per acquisition
- -Off-nadir for land vegetation
- -Maximizes signal-to-noise ratio over land and over water



(Muller-Karger et al., OCRT presentation, May 2016)

Conclusions

- Decadal Survey reports indicate that multiple strategies (=multiple RS assets) are needed to study coastal and inland aquatic environment.
- A mission like HyspIRI can address global extent, distribution and secular change.
- A mission like GeoCAPE may cover diel and tidal responses, but the spatial resolution may not be high enough for foundational species response.
- Technology exists to support RS observations of phenological change.
- Active RS could enhance information, especially in wetlands and terrestrial components.


THANK YOU

BACKUP

COASTAL WETLANDS: A VALUABLE NATURAL RESOURCE

Tidal marshes provide valuable ecological services, estimated at $14,397 USD per hectare per year globally.*

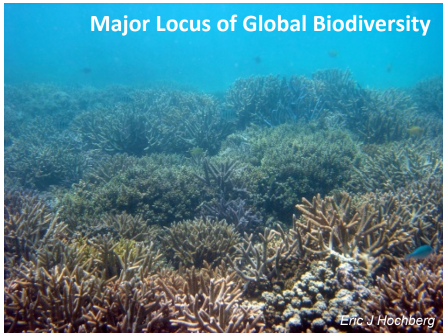
- **BIOGEOCHEMICAL CYCLING:**
  - One of the most productive biomes for **Carbon** uptake per area.
  - Uptake nutrients **N** & **P** from further up the watershed.
  - Can take up toxic substances before entering open water.
  - Major source of **CDOM** in coastal waters. (blue carbon)
  - Filter suspended sediment.
- **IMPORTANT ECOLOGICALLY:**
  - Habitat or nursery for many birds, fish, and other fauna.
  - Up to **1/2** of **N**. American bird species nest or feed in wetlands.*
  - **31%** of all plants species in ConUS.*
- **IMPORTANT ECONOMICALLY:***
  - Support industry worth hundreds of billions of USD.
  - Support hundreds of thousands of jobs in the USA.
- **PROTECT HUMAN HABITAT AND PROPERTY:**
  - Can absorbs wind wave energy of major storms.
  - An acre of wetland can store **1-1.5 x 10^6** gallons of flood water.*

* 2009 inflation-adjusted value (Bromberg-Gedan 2009)
* (see http://water.epa.gov/type/wetlands/outreach/upload/functions-values.pdf (EPA 2010) - 22 Oct 2014)

Coral Reef Background

Eric J Hochberg

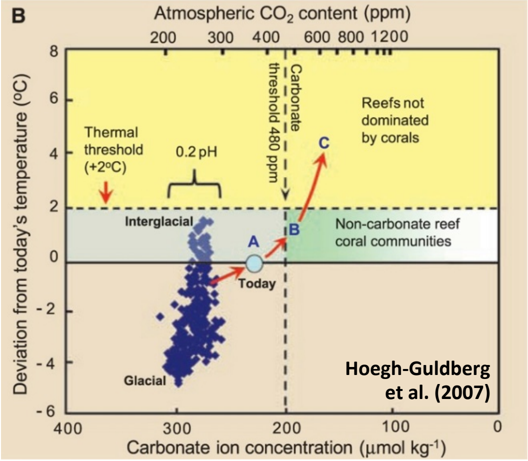
Importance

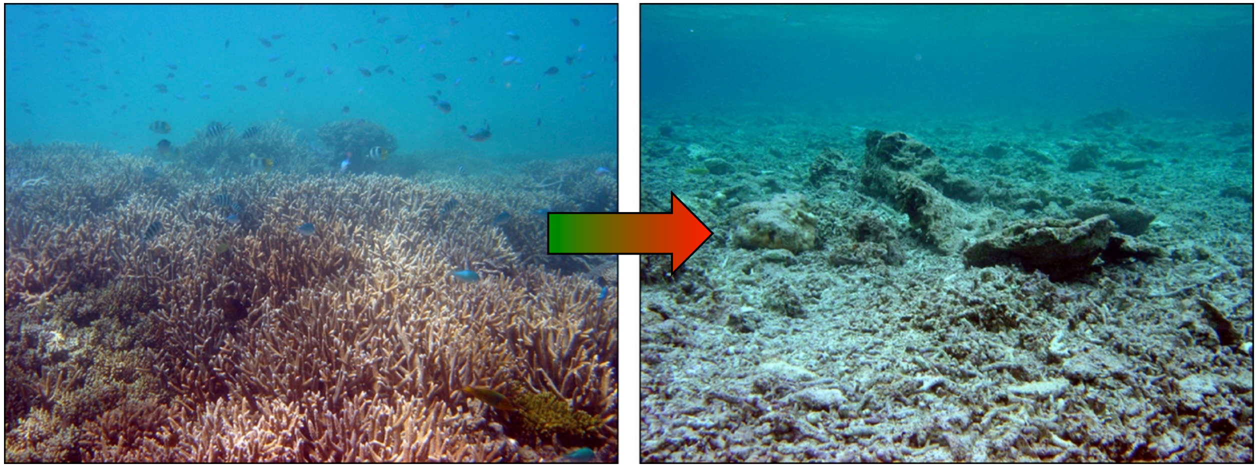


Coral reefs do not influence the short-term global carbon cycle, but...

Concern

...they are among the first ecosystems to respond critically and dramatically to climate change.



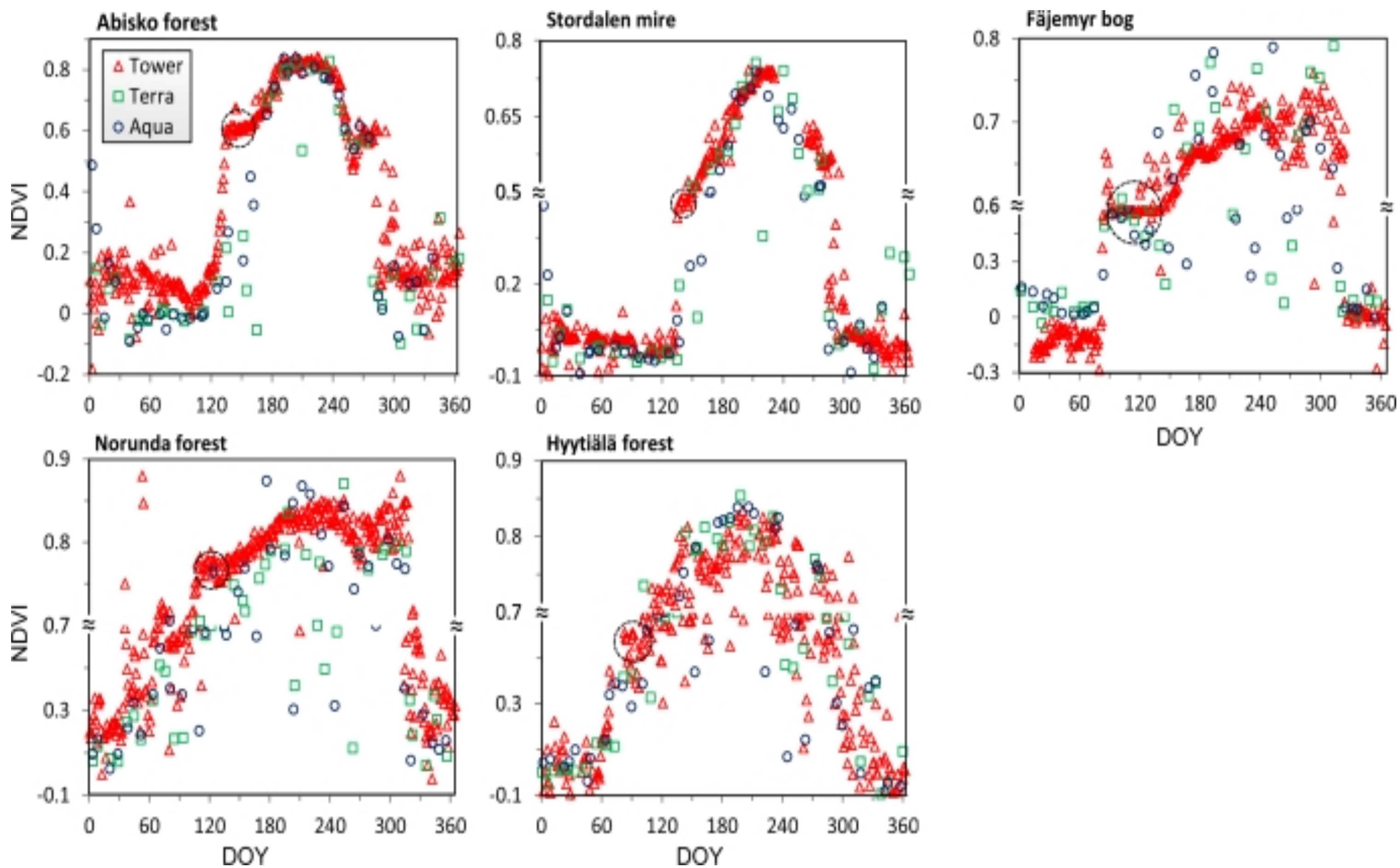


Climate change may exacerbate local impacts, leading to reef degradation worldwide.

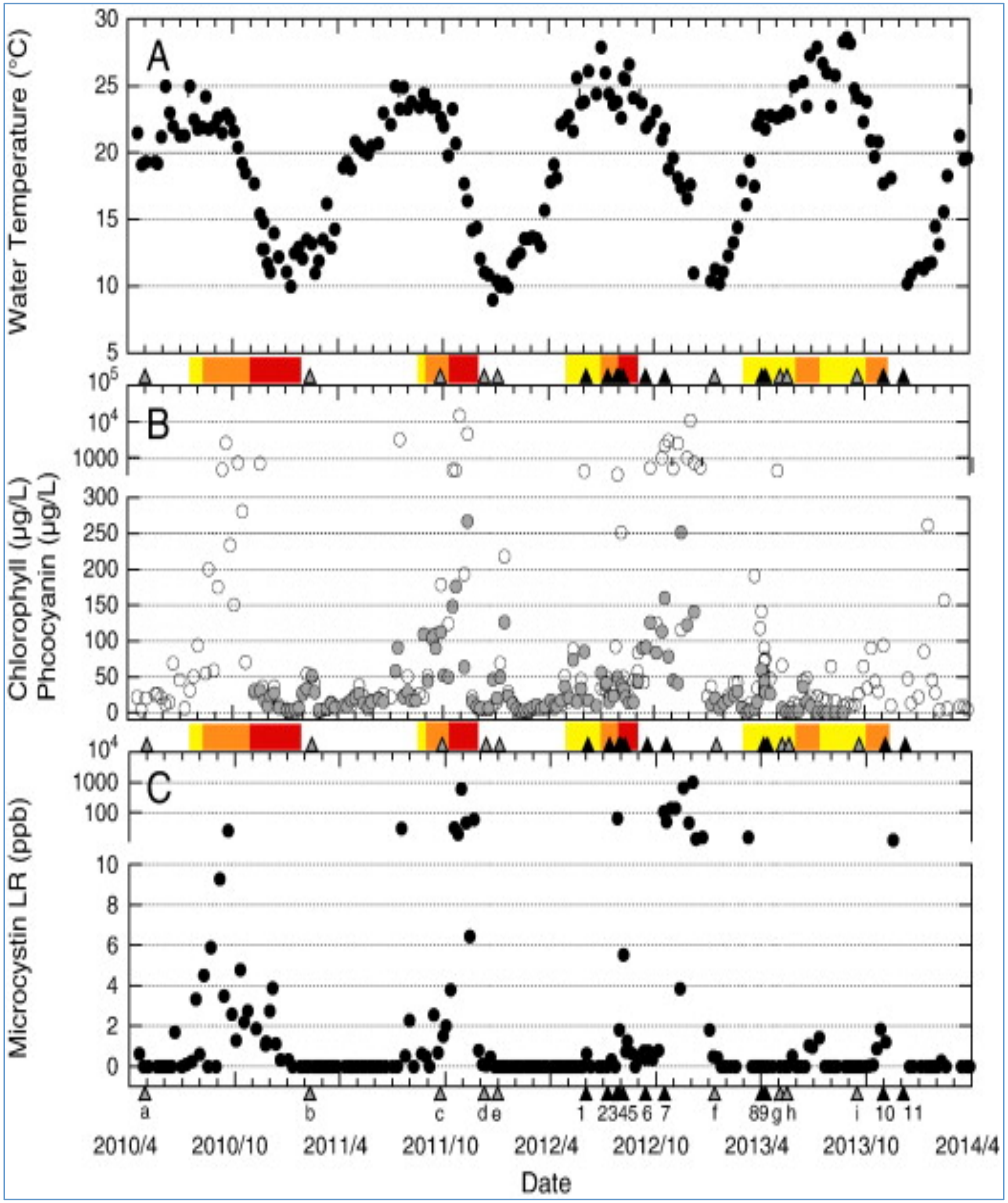

Eleven of the 15 largest cities in the world lie in coastal regions
In the US, 53% of the population lives near the coast
NickCPrior - Own work, CC BY-SA 3.0, https:
commons.wikimedia.org/w/index.php?curid=1444217

Our life and economy depend on freshwater supply and healthy coastal ecosystems

Phenology of terrestrial and wetland vegetation shows quick change with season and events



NDVI of forest canopy in Sweden, Finland, Denmark, and Norway. A ten-fold change occurs in less than a week in spring (Eklundh et al. 2011. An Optical Sensor Network for Vegetation Phenology Monitoring and Satellite Data Calibration. Sensors. 2011; 11(8): 7678–7709.)

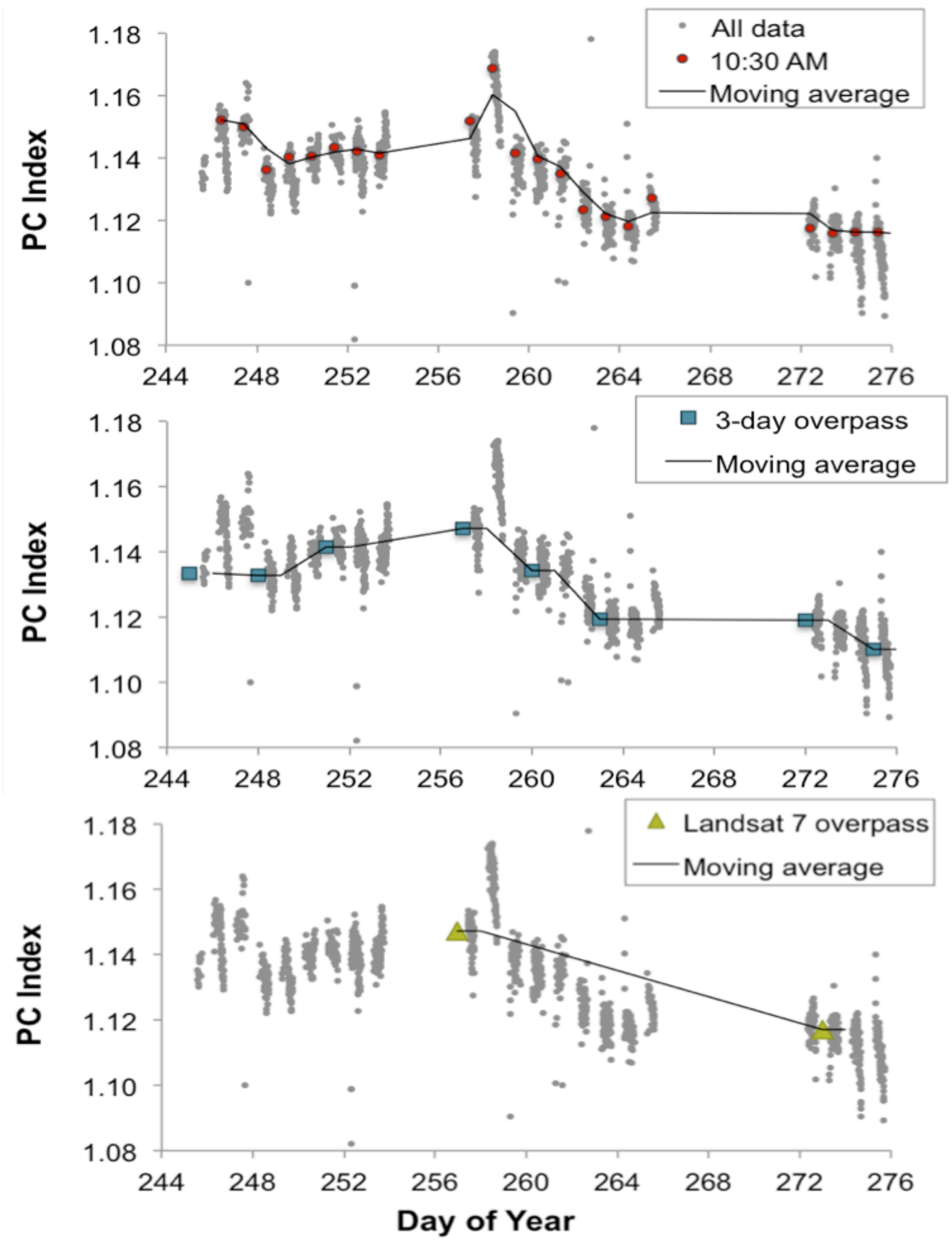


Phenology of aquatic communities

Rapid change in cyanobacteria concentrations in Lake Pinto, CA

Detectable using hyperspectral field data

[Kudela et al., 2015]



Measuring aquatic phenology

Cyanobacteria concentrations in Mantua Lake (Italy)

Rapid changes over a few days

Measurements every 3 days would capture changes in the concentration of phytoplankton, sediment load, and other water quality factors *at five times the Landsat frequency*

[after Hestir et al. 2015].

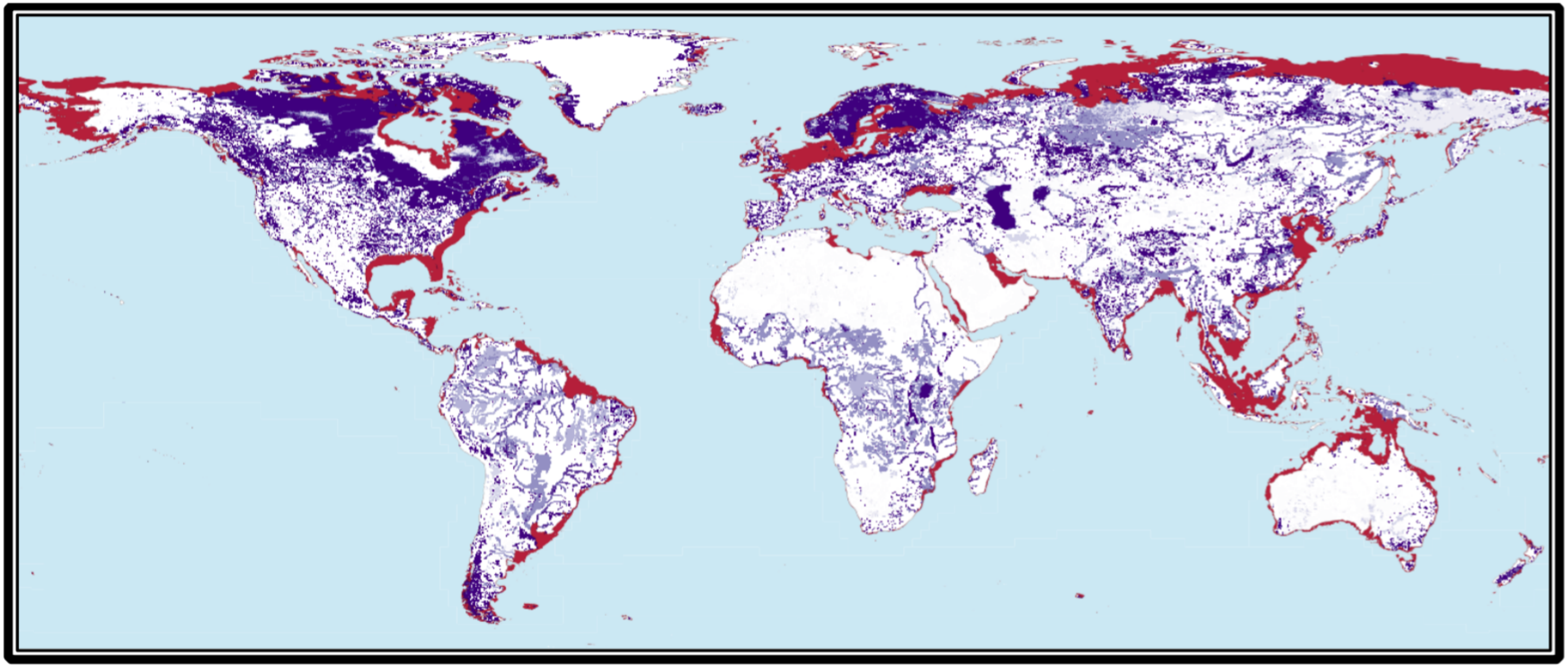
Example: EnMAP

If EnMAP were to be a global mission

- 27 day repeat **with ±5 deg cross-track pointing**
- 4-5 day revisit **by ± 30 deg cross-track pointing**
  - Issue: limited revisit for time series, and if so, at different cross-track angles for every collection.
  - Possibly uninterpretable!!
- But:
  - 5% or worse polarization sensitivity (bad news for ocean color since ocean radiance signal is ~1% of Top of Atmosphere radiance)
  - EnMap is on-demand only, like PRISMA, when launched

Coastal and inland aquatic science

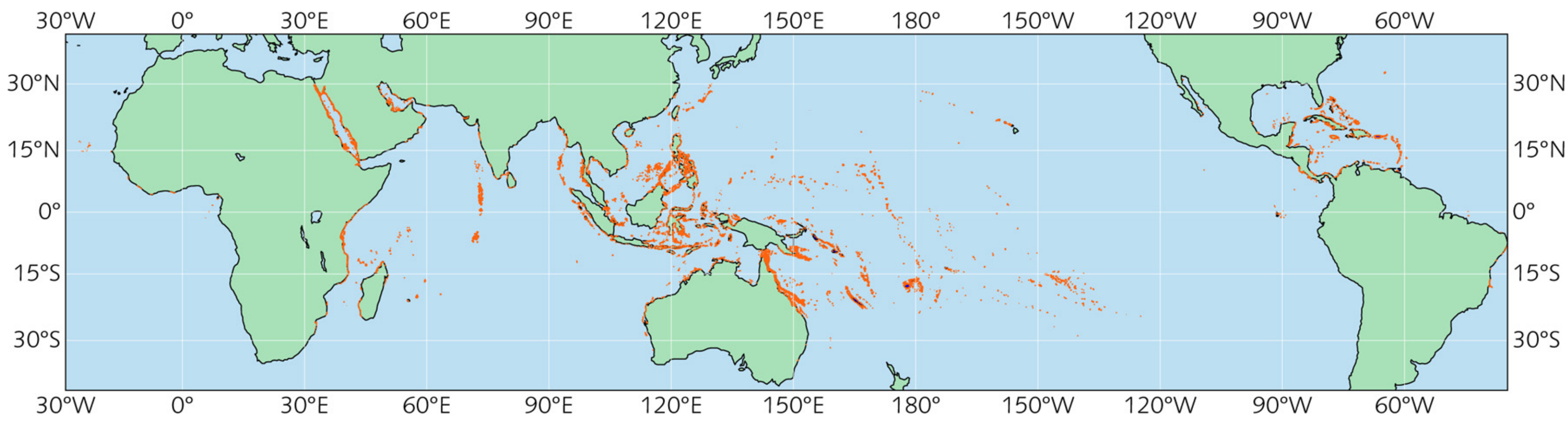
Coastal and inland ecosystems are distributed world-wide, but actual areal extent for any particular kind of habitat is currenly highly uncertain.



Global distribution of coastal and inland aquatic ecosystems. Red indicates regions where water depth is less than 50 m and where land elevation is less than 50 m. Light to dark violent gives the concentration of inland wetlands, lakes, rivers and other aquatic systems. Increased darkness means greater percentage of areal coverage for inland aquatic ecosystems (UNEP-WCMC, 2005).

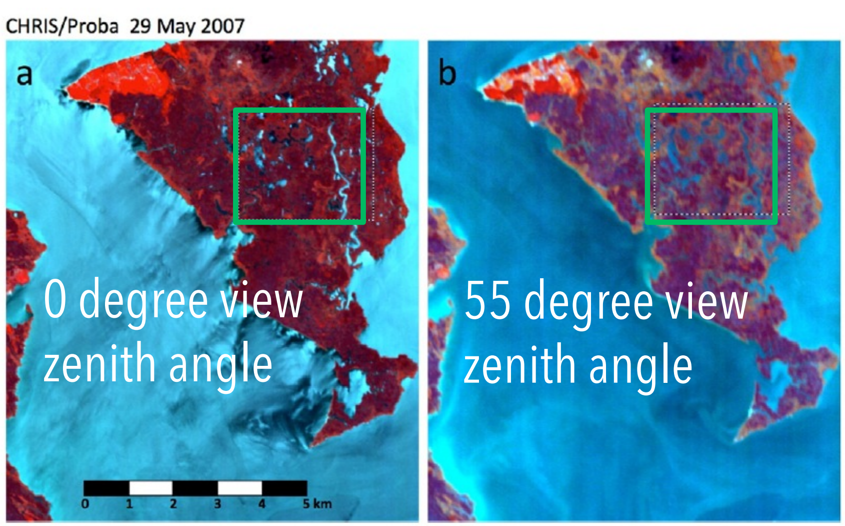
Coastal and inland aquatic science

For instance, only a small fraction of all coral reefs have been surveyed to determine their health, or the impact of increasing temperature and acidity.



Wetlands and aquatic targets at different view angles

Higher reflectance when looking straight down because you see water in addition to vegetation



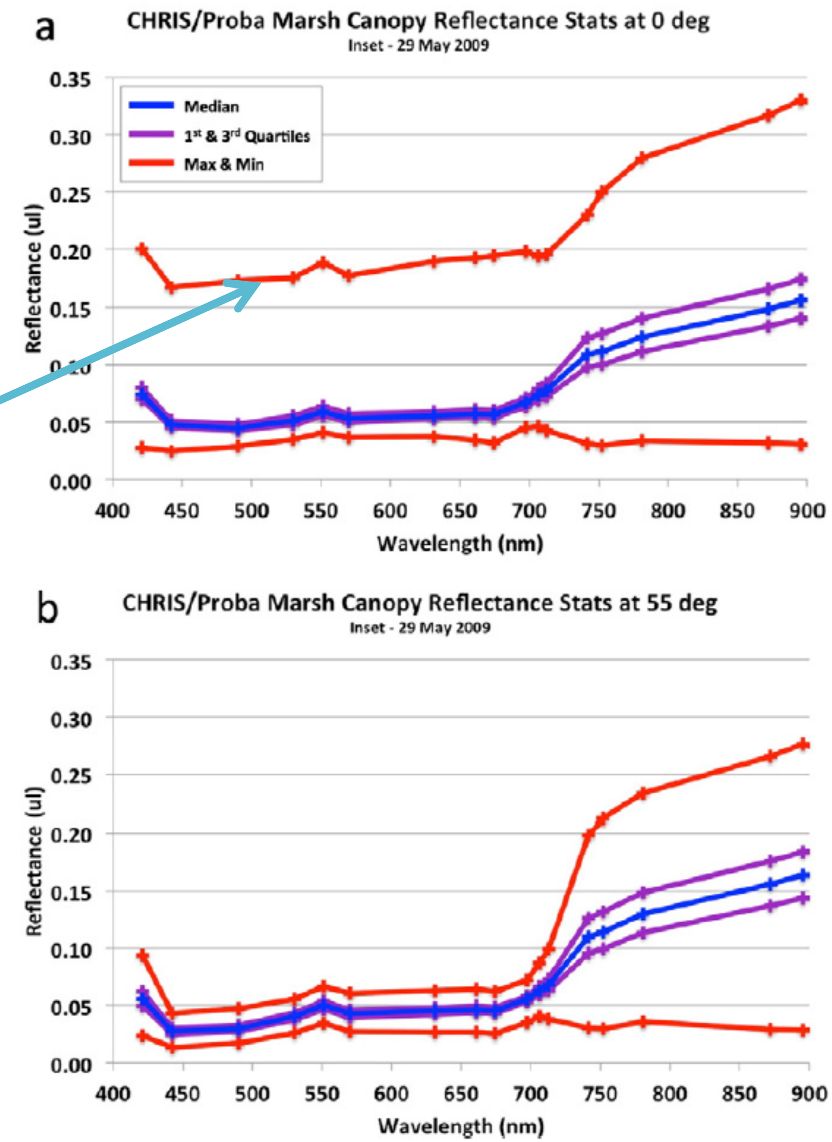


Fig. 6. Spectra extracted from regions highlighted by boxes in Fig. 5. (a) At 0° nominal view zenith angle, glint produces very high values across the spectrum, evidenced by the maximum spectral curve. (b) At 55° nominal view zenith angle, the glint effect is greatly reduced.

[Turpie et al 2015]

Wetland BRDF effects (bidirectional reflectance distribution function)

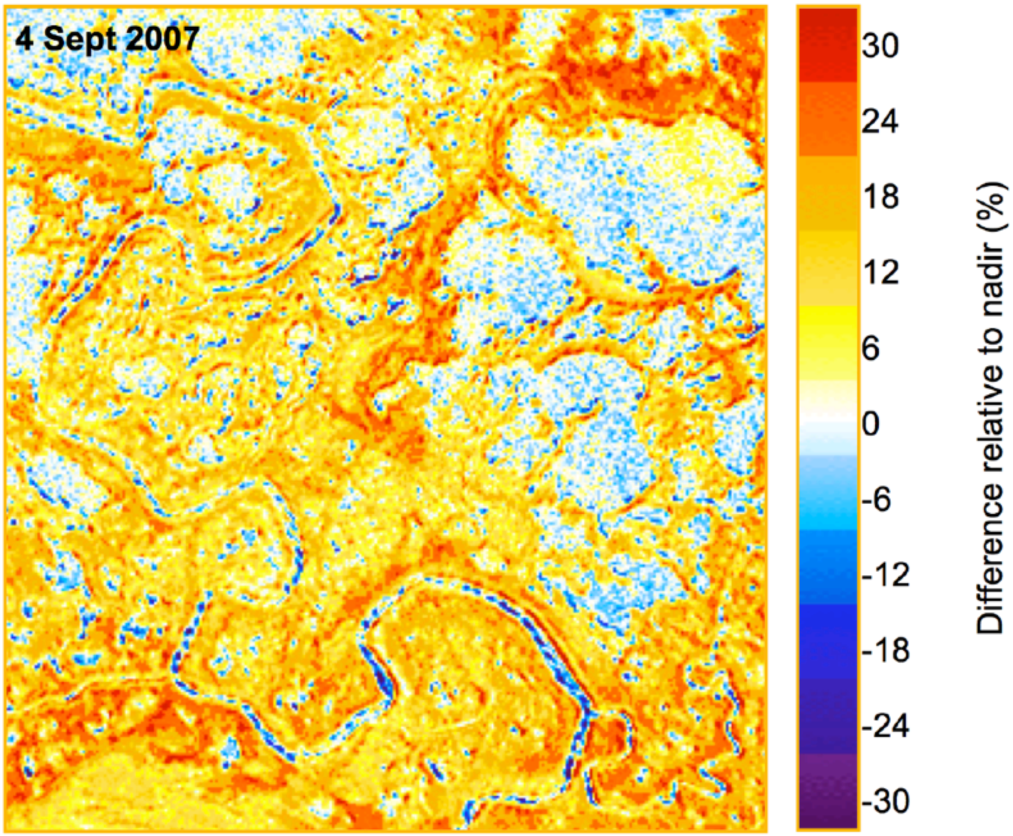


FIGURE 1 - Radiance difference between ASTER 3N and 3B

Yellow and red: Emergent veg'tn.	White and light blue: water

1) Emergent vegetation:

More reflective off-nadir than at nadir

Issue:
You see water (specular reflection) when looking straight down on wetland vegetation

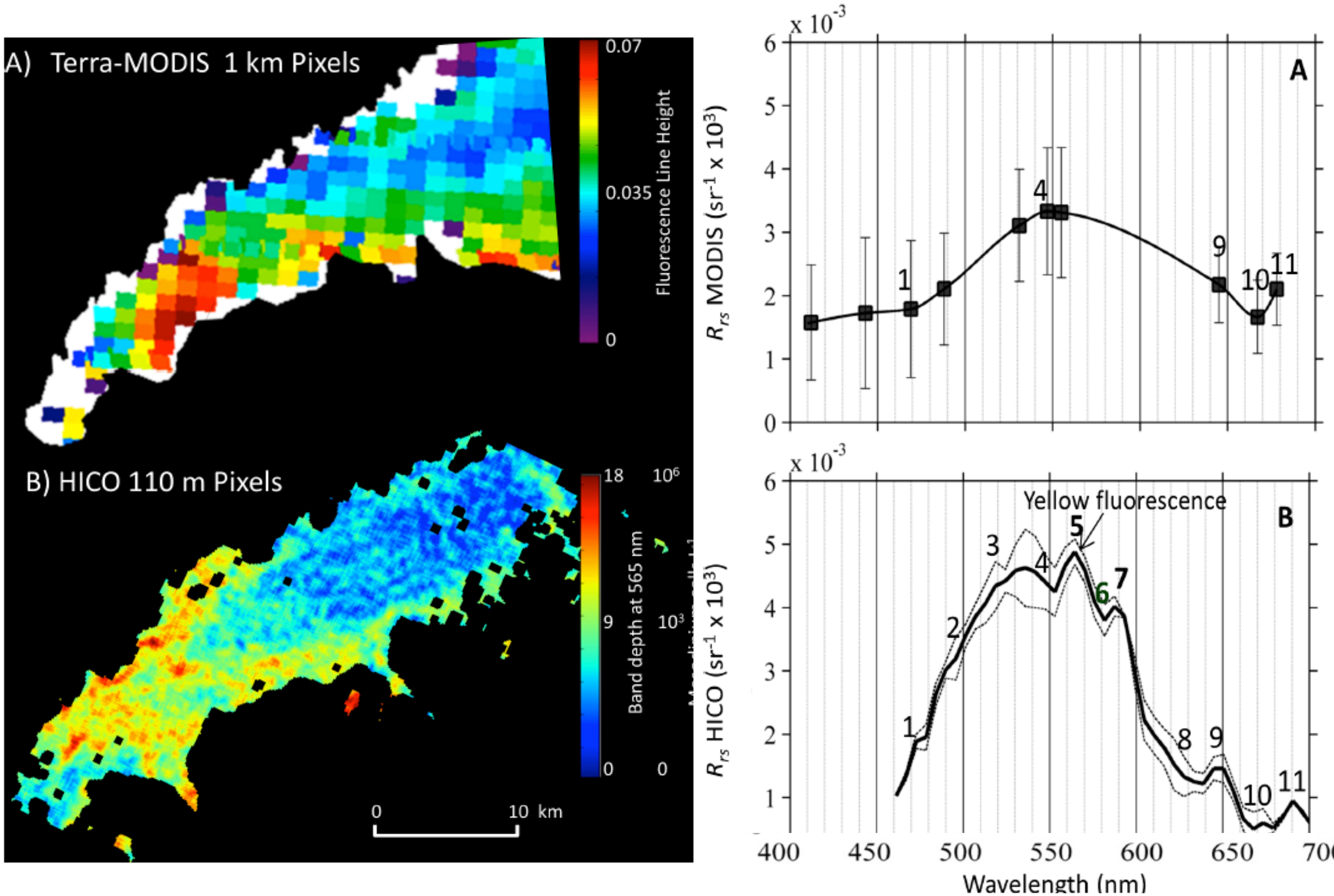
2) Open water:

Smaller radiance differences across wide range of view angles (c.f. SeaWiFS, MODIS scans, etc.)

[From Kevin Turpie]

High spectral resolution helps separate living from non-living water constituents

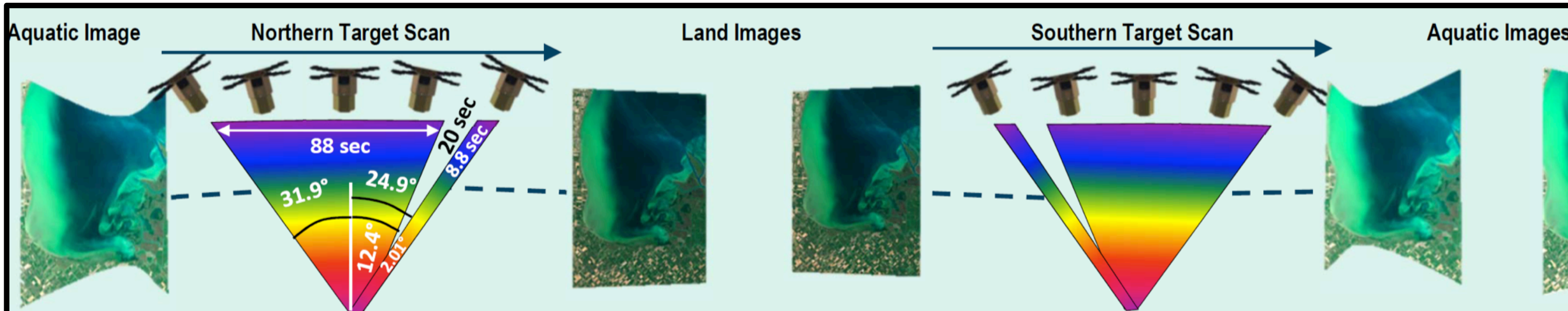
- Chlorophyll from CDOM
- Different small organisms (ciliates from phytoplankton)



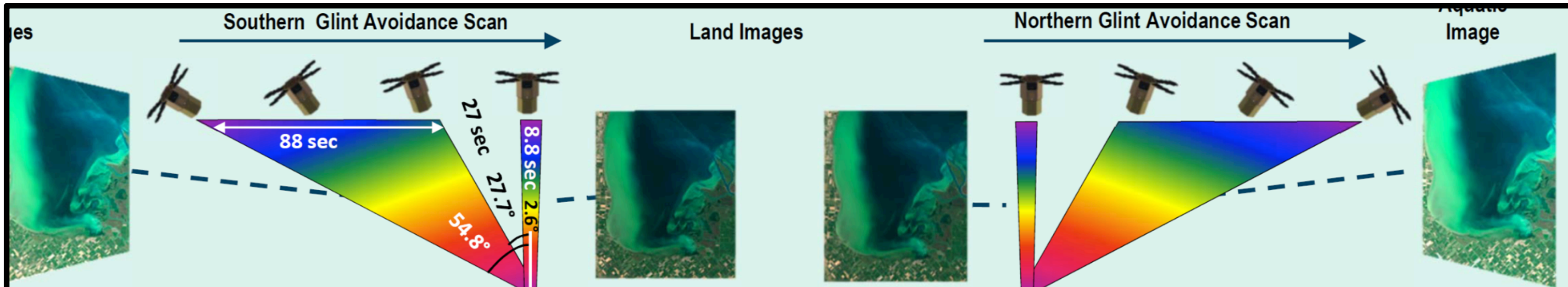
HICO shows *Mesodinium rubrum* bloom because it has fluorescence information provided by hyperspectral data

[Dierssen et al 2015]

Same geometry for each target including glint avoidance



PISCES employs 4 unique scan types during observations to optimize science return from each target. Each scan produces a high SNR image of ocean/aquatic environments as well as a faster image focused on land and emergent vegetation. The S/C rotates through a pre-defined attitude profile to maintain the required instrument pointing and integration time (Ex. F-2F).



For northern latitudes the high SNR scan is produced first, vice versa for southern targets. Where sunlight glint is an issue due to solar zenith angle, the pointing profile is adjusted and the order of images reversed. Normal scans take ~117 sec and glint avoidance scans ~124 sec. Scan types for each observation are predetermined by the mission planning software for each 6-month profile.

International Planned OC Sensors

SENSOR	AGENCY	SATELLITE	SCHEDULED LAUNCH	SWATH (km)	SPATIAL RESOLUTION (m)	# OF BANDS	SPECTRAL COVERAGE (nm)	ORBIT
OLCI	ESA/ EUMETSAT	Sentinel 3A	Oct 2015	1270	300/1200	21	400 - 1020	Polar
COCTS CZI	CNSA (China)	HY-1C/D (China)	2015	2900 1000	1100 250	10 10	402 - 12,500 433 -885	Polar
SGLI	JAXA (Japan)	GCOM-C	2016	1150 - 1400	250/1000	19	375 - 12,500	Polar
COCTS CZI	CNSA (China)	HY-1E/F (China)	2017	2900 1000	1100 250	10 4	402 - 12,500 433 - 885	Polar
HSI	DLR (Germany)	EnMAP	2017	30	30	242	420 - 2450	Polar
OCM-3	ISRO (India)	OCEANSAT-3	2018	1400	360 / 1	13	400 - 1,010	Polar
OLCI	ESA/ EUMETSAT	Sentinel-3B	2017	1265	260	21	390 - 1040	Polar
VIIRS	NOAA /NASA (USA)	JPSS-1	2017	3000	370 / 740	22	402 - 11,800	Polar
Multi-spectral Optical Camera	INPE / CONAE	SABIA-MAR	2019	200/2200	200/1100	16	380 - 11,800	Polar
GOCI-II	KARI/KIOST (South Korea)	GeoKompsat 2B	2019	1200 x 1500 TBD	250/1000	13	412 - 1240 TBD	Geostationary
OCI	NASA	PACE	2022/2023	*	*	*	*	Polar
HYSI-VNIR	ISRO (India)	GISAT-1	*(planned)	250	320	60	400-870	Geostationary (35,786 km) at 93.5°E
OES	NASA	ACE	>2020	TBD	1000	26	350-2135	Polar
Coastal Ocean Color Imaging Spec (Name TBD)	NASA	GEO-CAPE	>2022	TBD	250 - 375	155 TBD	340-2160	Geostationary

From Heidi Dierssen

Science Traceability Matrix (partial)

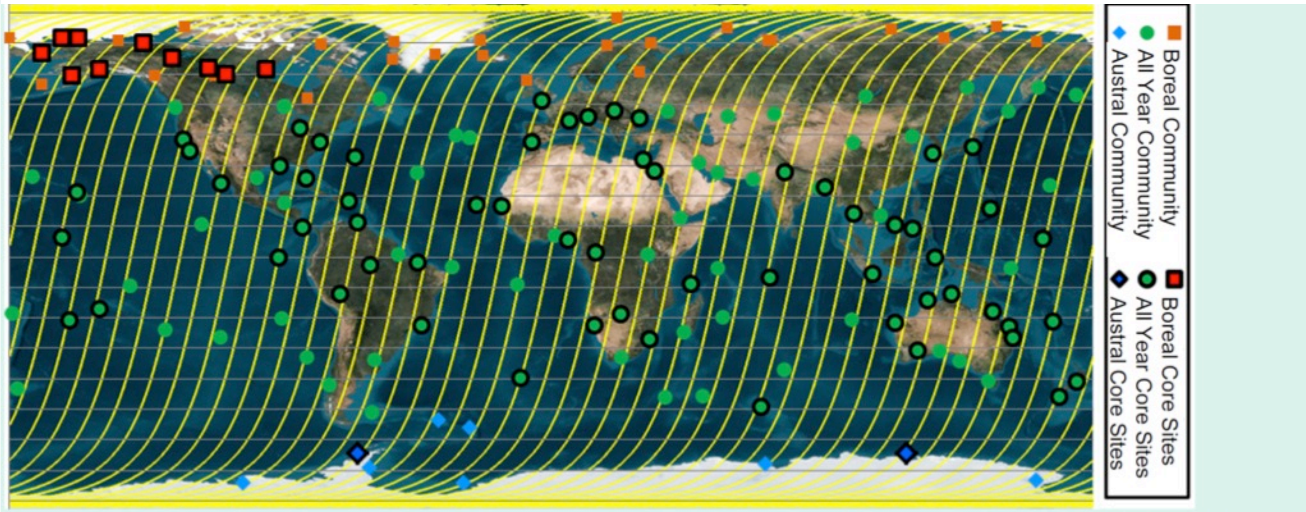
Goal: Characterize short-term changes in the functional biodiversity and biogeochemical cycles of coastal and wetland ecosystems, from canopy to benthos, and trace these changes to their underlying environmental influences.

Objectives:

- Overall: Determine how phenologies of key coastal, wetland, and inland water ecosystems change in response to natural and human-induced environmental factors.
- Coastal Zone Blooms: Evaluate the quality, diversity, and productivity of coastal aquatic habitats as a function of nutrient inputs, light, and other physical & biotic factors.
- Wetland Vegetation: Determine drivers of wetland phenology & the relationship between wetland phenology and organic & inorganic material inputs to adjacent waters.
- Benthic Communities: Measure the relationship between the composition and health of shallow submerged (benthic) communities and the ecology of adjacent wetlands.

Observational Regime	Organic/Physical Features	Measurement Requirement
1. Aquatic Habitats		
Marine Coastal: Water and water-land boundary areas • Estuaries • Corals • Seagrasses • Mangrove Forests • Salt Marshes and Salt Flats • Clear ocean • Small Islands	Phenology, community composition, and changes in water quality, including specifically those listed below.	SNR > 1000, ocean radiance 400-710 nm
		Abs. radm. cal < 5%, Relative cal < 0.5%
		Polarization sensitivity < 1.2%
		Spatial resolution < 60 m/pix Field of View (FOV) > 20x20 km
		Stray light <0.5% at 5 pixels from edge of bright area, <0.1% at 33 pixels
		VNIR does not saturate on clouds
		Bands 1240 nm, 2125 nm SNR > 250, > 100
	Phytoplankton, diatoms, other water-borne life: Concentration, size, functional groups	Spectral range 400-885 nm, < 2 nm/band (< 3 nm FWHM), stability < ±0.3 nm, keystone < 0.1 pix
	Colored dissolved organic matter (CDOM); Total suspended solids, detritus Turbid waters	Spectral range 400-600 nm, 50 nm/band
	Bathymetry	Spectral range 400-700 nm, 20 nm/band
	Benthos, shallow reefs, submerged vegetation, kelp and seagrass beds	Spectral range 400-650 nm, < 2 nm/band (<3 nm FWHM), stability < ±0.3 nm, keystone < 0.1 pixel
	Floating vegetation	Spectral range 600-885 nm, SWIR
Inland Coastal: Wetlands and Marsh • Fresh Water Environments	Differentiate land and water-borne vegetation	Spectral range 400-885 nm, SWIR Emission angle variation < 5º in image
	Relative fraction of water, vegetation, soil, sediment	
2. Land Habitats		
Riparian and Watershed Environments High latitude	Plant life form (tree, grass, canopy, etc) Biogeochemistry Vegetation density and structure Inundation level, soil type, carbon content	Emission angle variation < 5 deg in image Spatial resolution < 60 m/pix Field of View (FOV) > 20x20 km Spectral range 400-885 nm, < 2 nm/band (3 nm FWHM), stability < ±0.3 nm, keystone < 0.1 pix SWIR 1240 and 2125 nm VNIR does not saturate on clouds
Urban Areas Megacities	Managed wetlands, farmlands, wastewater	
3. Atmosphere		
Atmosphere above coastal marine and inland environments, rural and urban	Aerosol type and composition variations	Oxygen A and B bands, < 2 nm/band Spectral range 400-885 nm, 20 nm/band SWIR 1240 and 2125 nm Polarization sensitivity < 1.2% Spatial resolution < 150 m/pix VNIR does not saturate on clouds
	Optical thickness, vertical distribution	
	Short term/local change	
	Atmospheric correction/adjacency	
	Cloud cover and cloud detection	
General		
All habitats and environments	All physical and organic features	Measure seasonal changes
		Frequency of clear observations 5/month
		Observe several of each type of target

Sample (mock) target locations showing seasonal changes in hemisphere for high latitude acquisitions based on illumination



Sample monthly target acquisitions showing seasonal changes, accounting for regional cloud cover

Orbit	A. Estuaries	B. Corals	C. Seagrasses	D. Mangrove Forests	E. Salt Marshes and Salt Flats	F. Fresh Water Environm	G. High Latitude Environments	H. Coastal Megacities	I. Small Islands	J. Clear Ocean Water Tar
3-Day Total	16	37	11	18	29	26	44	5	25	8
Monthly Total	160	370	110	180	290	260	440	50	250	80
Cloud Losses	45%	37%	42%	40%	43%	46%	52%	46%	43%	37%
Downlink Losses	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
Est. Monthly Good	86	228	63	105	161	137	208	26	140	49
Req'd Target Types 5 obs/month	10	7	7	7	7	10	7	4	7	6
Req'd Monthly Total	50	35	35	35	35	50	35	20	35	30
Margin	**72%**	**551%**	**80%**	**200%**	**360%**	**174%**	**494%**	**30%**	**300%**	**63%**