Distinguishing Macrophytes from Other Sources of Reflectance in an Optically Complex, Glacially-Impacted Fjord System in Greenland Using Sentinel-2

Dan Carlson - KDD
NOCCG Seminar
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Helmholtz-Zentrum hereon

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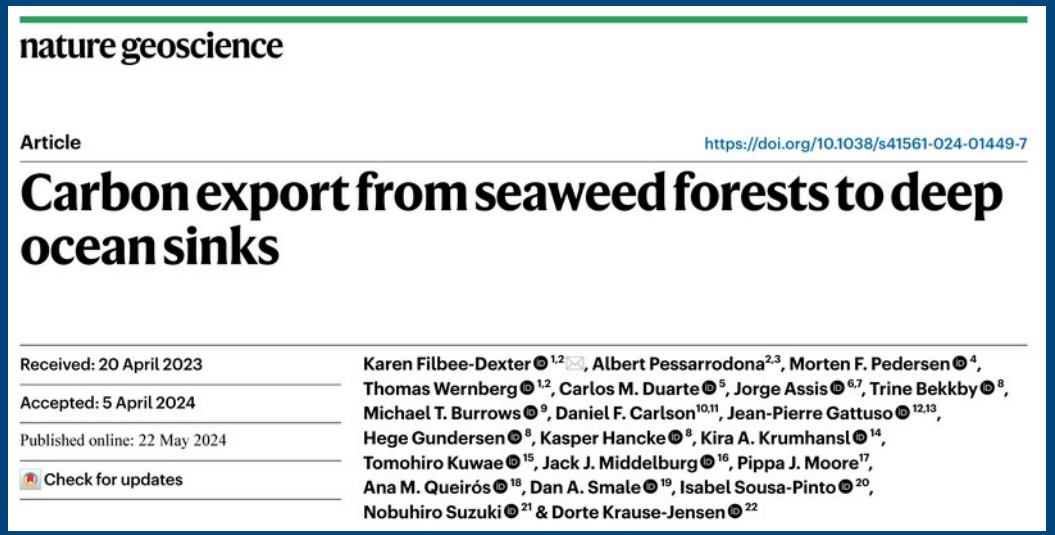
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Mapping intertidal macrophytes in fjords in Southwest Greenland using Sentinel-2 imagery

Daniel F. Carlson [a,*], Antoni Vivó-Pons [a,b], Urs A. Treier [c], Eva Mätzler [d], Lorenz Meire [e,f], Mikael Sejr [a,g], Dorte Krause-Jensen [a,g]



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Carbon export from seaweed forests to deep ocean sinks

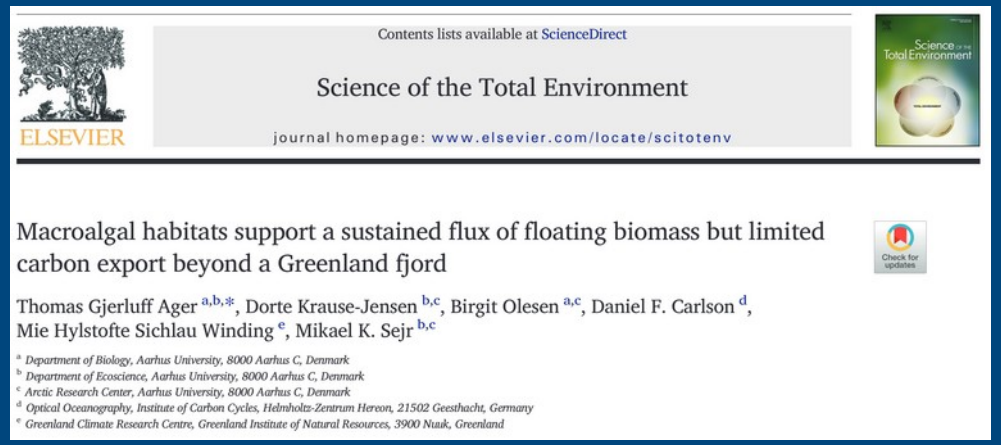
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Karen Filbee-Dexter [1,2], Albert Pessarrodona [2,3], Morten F. Pedersen [4], Thomas Wernberg [1,2], Carlos M. Duarte [5], Jorge Assis [6,7], Trine Bekkby [8], Michael T. Burrows [9], Daniel F. Carlson [10,11], Jean-Pierre Gattuso [12,13], Hege Gundersen [8], Kasper Hancke [8], Kira A. Krumhansl [14], Tomohiro Kuwae [15], Jack J. Middelburg [16], Pippa J. Moore [17], Ana M. Queirós [18], Dan A. Smale [19], Isabel Sousa-Pinto [20], Nobuhiro Suzuki [21] & Dorte Krause-Jensen [22]



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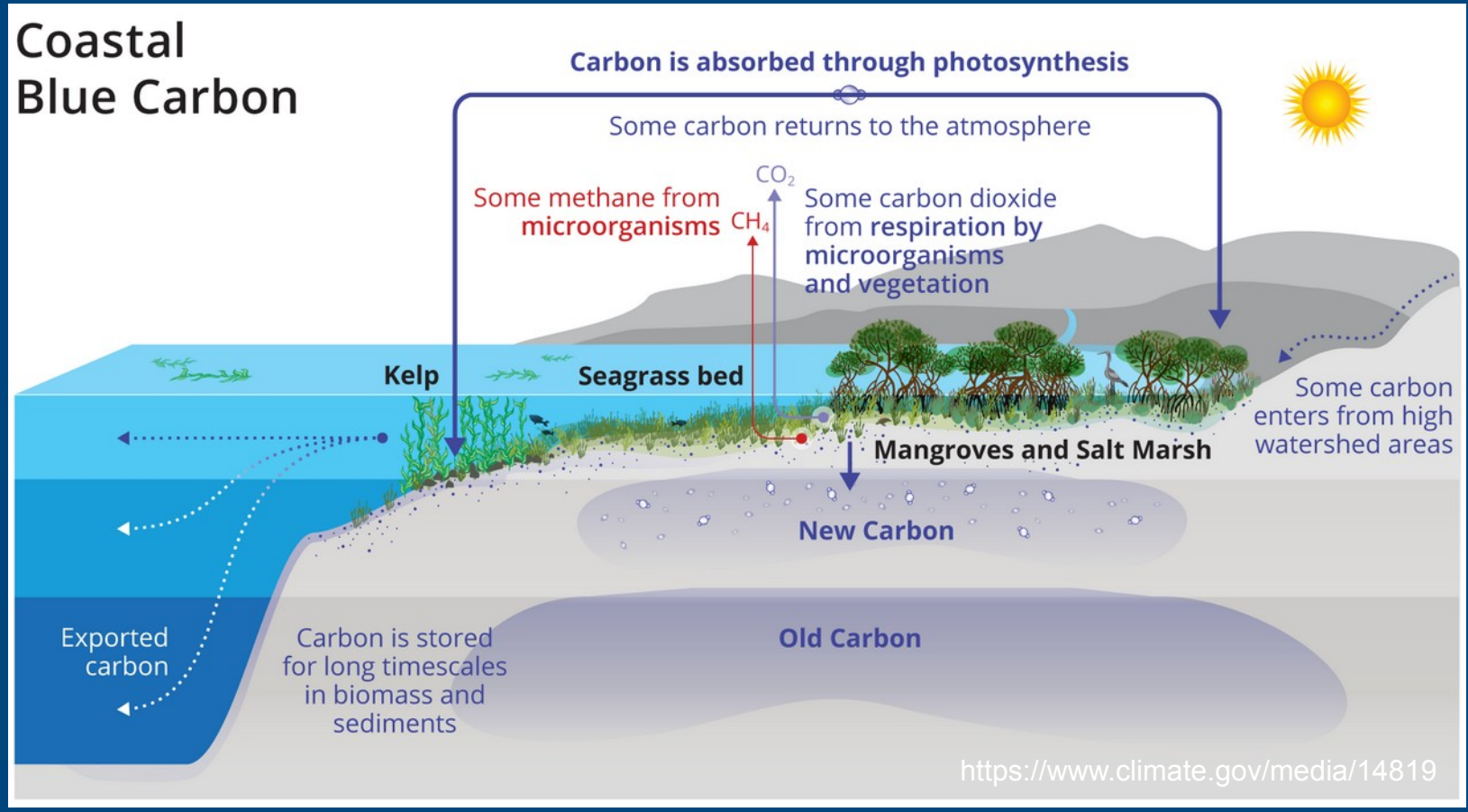
Macroalgal habitats support a sustained flux of floating biomass but limited carbon export beyond a Greenland fjord

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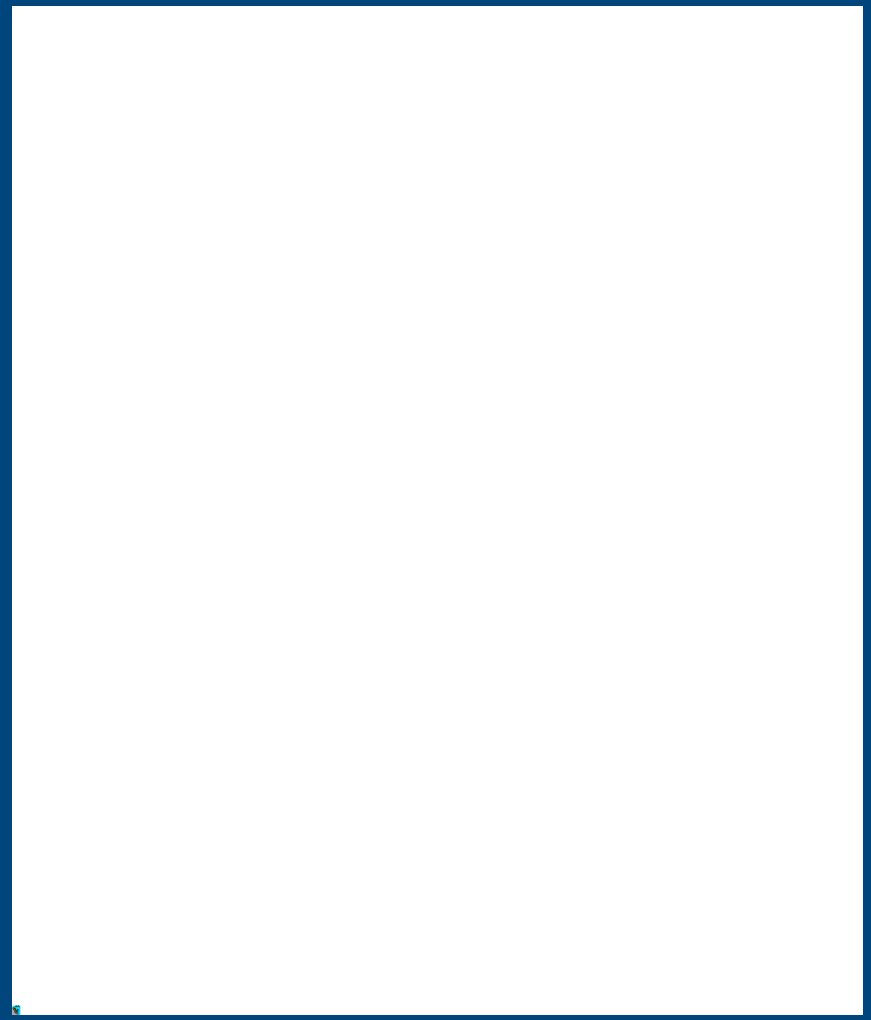
Motivation

- Traditional blue carbon habitats
- Seagrass, mangroves, and salt marshes
- CO2 absorbed and carbon stored in biomass and in soil
- Macroalgae may also export large amounts of carbon to deep ocean sinks



Macroalgae’s Role in the Ocean Carbon Cycle

- Macroalgae are widely distributed and very productive.
- Macroalgal carbon export pathways are more complicated.
- Potential for burial is limited for macroalgae that grow on rocky substrate.
- Export of macroalgal-carbon is a multi-step process
- Macroalgae must become detached from substrate,
- Detached macroalgae must be transported away from shore.
- Detached macroalgae transported away from shore must enter seabed sediments or abyssal waters.
- Steps must be completed before remineralization.
- Latest estimates indicate that 4-44 Tg C can be sequestered for 100 years (Filbee-Dexter et al., 2024).
- Estimates of macroalgal carbon export can be improved by developing large-scale mapping and tracking capabilities.



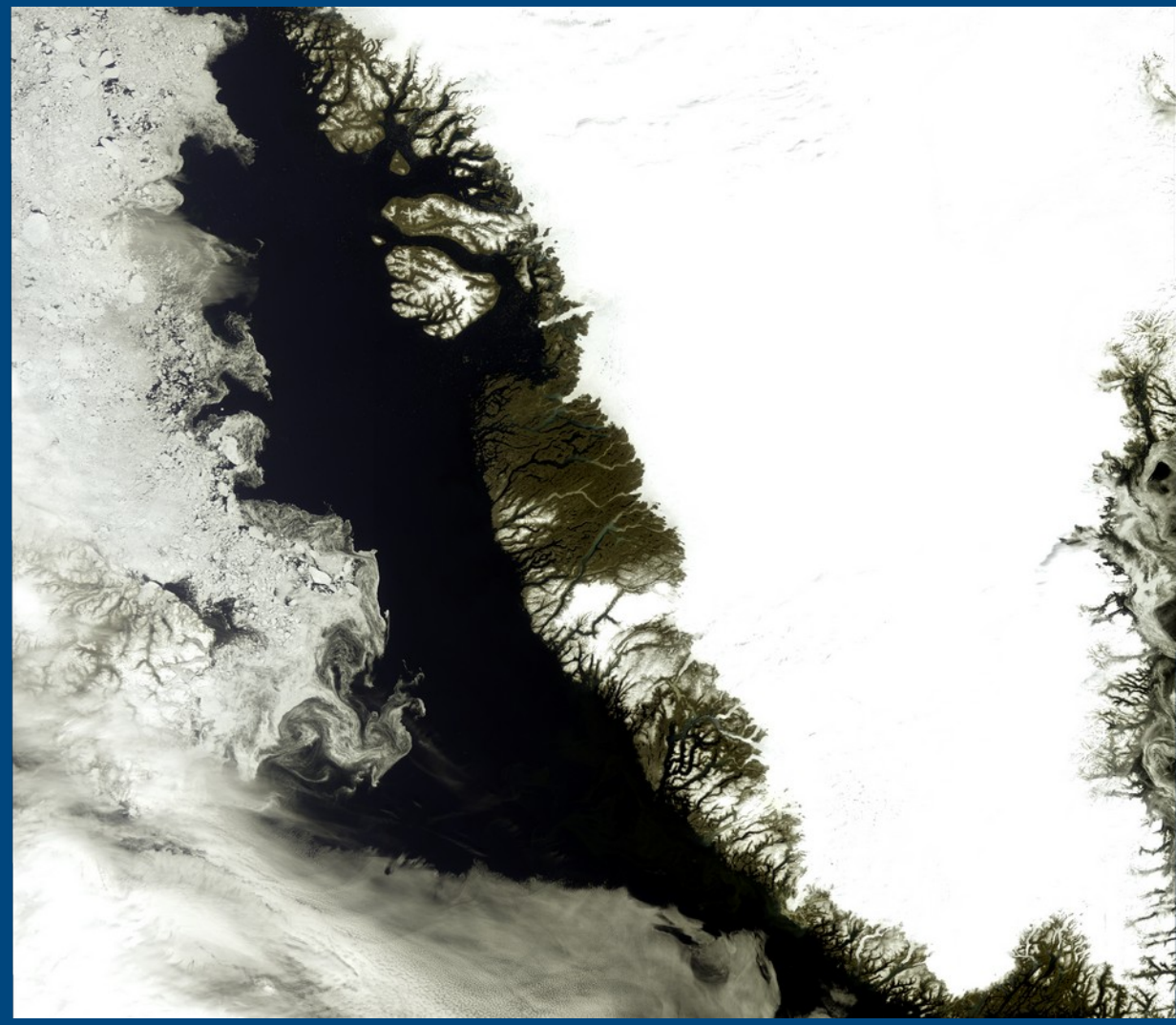
Why Greenland?

- World‘s biggest island
- Extensive and rocky coastline
- HSM project poleward expansion of macroalgae due to climate change
- Extensive fjord systems with high sedimentation rates
- Adjacent to deep water formation sites in the Labrador and Irminger Seas
- Potential for macroalgae carbon export



Satellite Remote Sensing

- Fjords and coasts are changing
- Baseline maps of macroalgae distribution are lacking
- Large-scale mapping and monitoring tools are urgently needed
- Satellite remote sensing can map coastal macrophytes
- Limited by clouds and sun angle
- Limited to surface ocean, intertidal, and shallow subtidal
- Max depth in coastal zone depends on optically active substances in overlying water column



Sentinel-2 Multispectral Imager

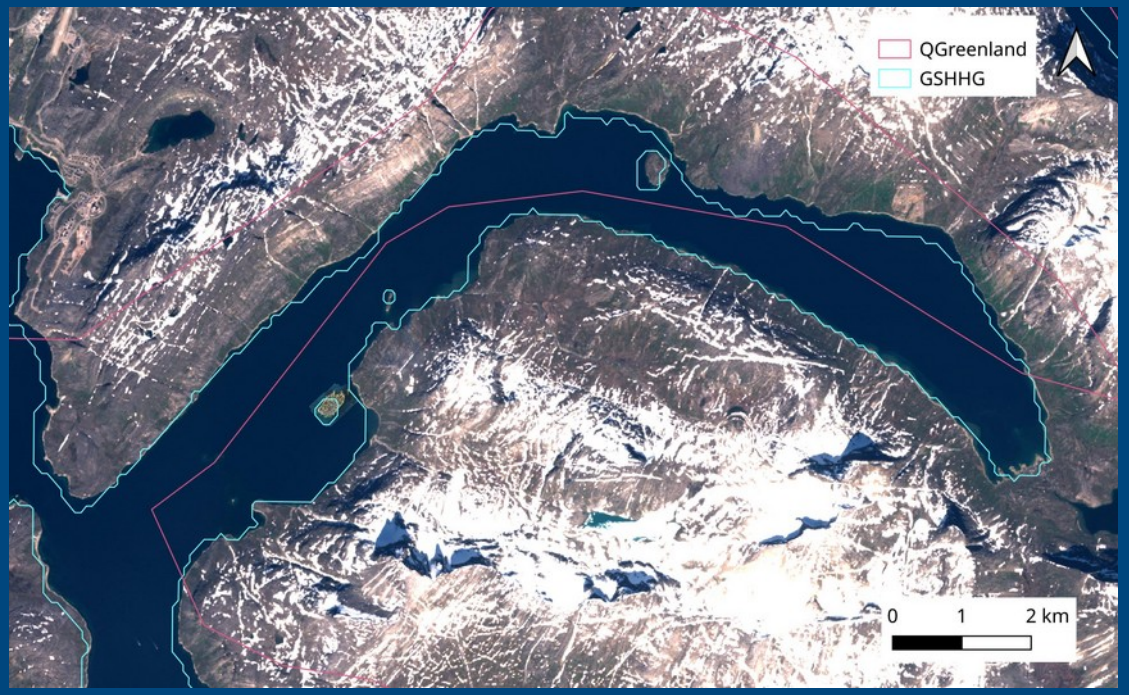


- 2 satellites (S2-A/B) (Maybe 3?)
- 13 bands at 10-60 m resolution
- 10 m imagery in RGB + NIR
- Revisit time 2-3 days at high latitudes
- Used to map intertidal macroalgae and kelp in temperate and high-latitude coasts – but not in Greenland – Until Now!

Remote Sensing Challenges

- Greenland‘s fjords and coasts pose unique challenges that remote sensing community only recently started to address
- Steep topography
- Icebergs and turbidity
- Macroalgae inhabit narrow coastal band and canopies do not extend to the surface
- Limited Supporting Data (bathymetry, coastlines, tides)







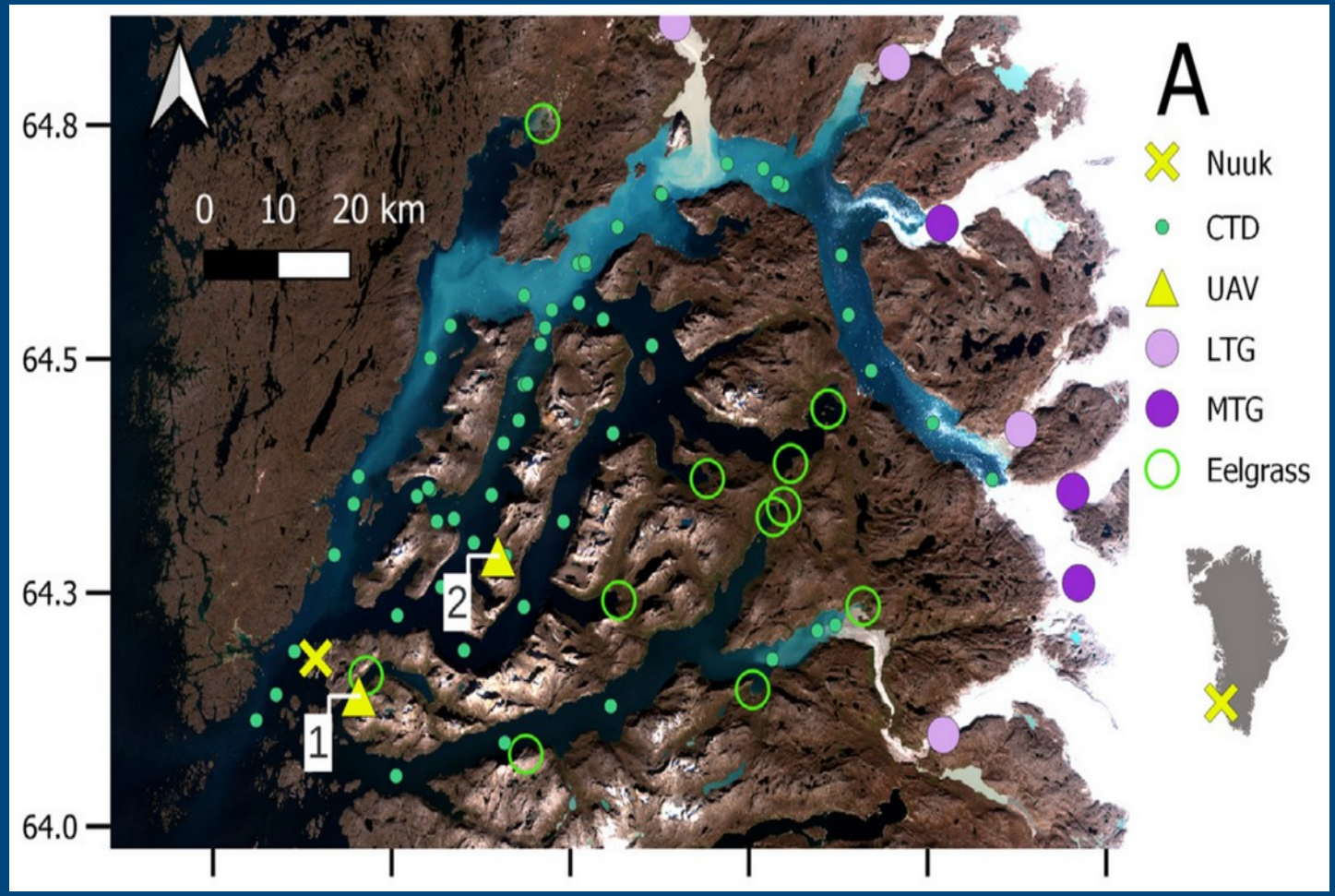
Remote Sensing Objectives

- Use S2 to detect intertidal macrophytes exposed at low tide.
- Determine if patches of floating macroalgae are large enough to be detected in 10 m S2 images.
- Evaluate the impact of ice and turbidity on the distribution of intertidal macroalgae in Nuup Kangerlua and Ameralik.



Study Area – Nuup Kangerlua and Ameralik

- Best-studied fjord systems in Greenland
- Combined marine area 2770 km²
- 1300 km coastline
- 3 marine terminating glaciers
- 4 land-terminating glaciers
- Max depth ~700 m
- Intertidal macroalgae - *Ascophyllum nodosum* and *Fucus spp*
- Eelgrass (*Zostera marina*) also present
- S2 can‘t distinguish between macroalgae and eelgrass



Vegetation Indices

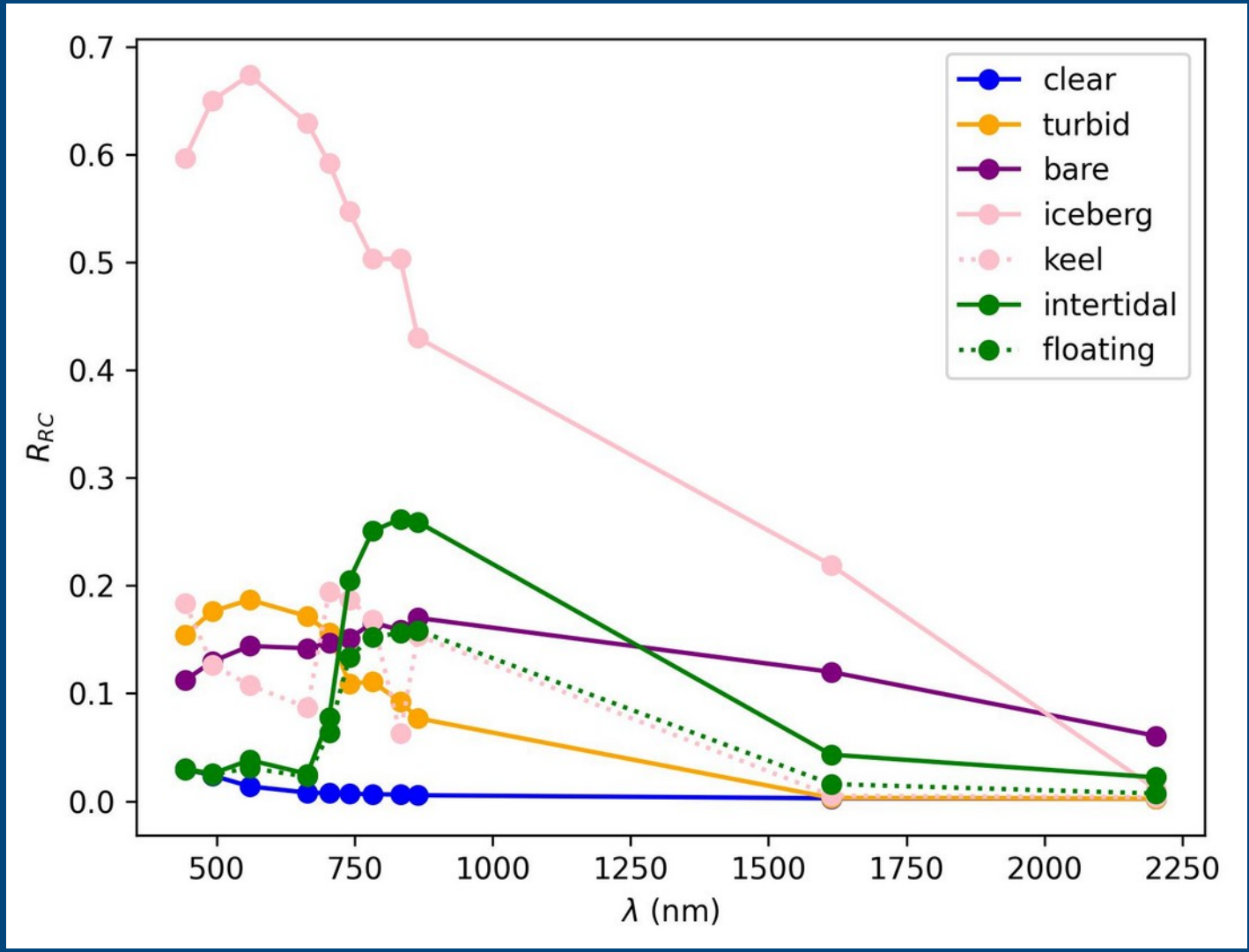
$$NDVI = (R_{NIR} - R_{red})/(R_{NIR} + R_{red})$$

$$EVI = 2.5^{*}(R_{NIR} - R_{red})/(R_{NIR} + 6^{*}R_{red} - 7.5^{*}R_{blue} + 1)$$

$$FAI = R_{rcNIR} - R'_{RC\,NIR}$$
$$\text{where}\, R'_{RC\,NIR} = R_{RC\,red} + (R_{RC\,SWIR} - R_{RC\,red}) * (\lambda_{NIR} - \lambda_{red})/(\lambda_{SWIR} - \lambda_{red})$$

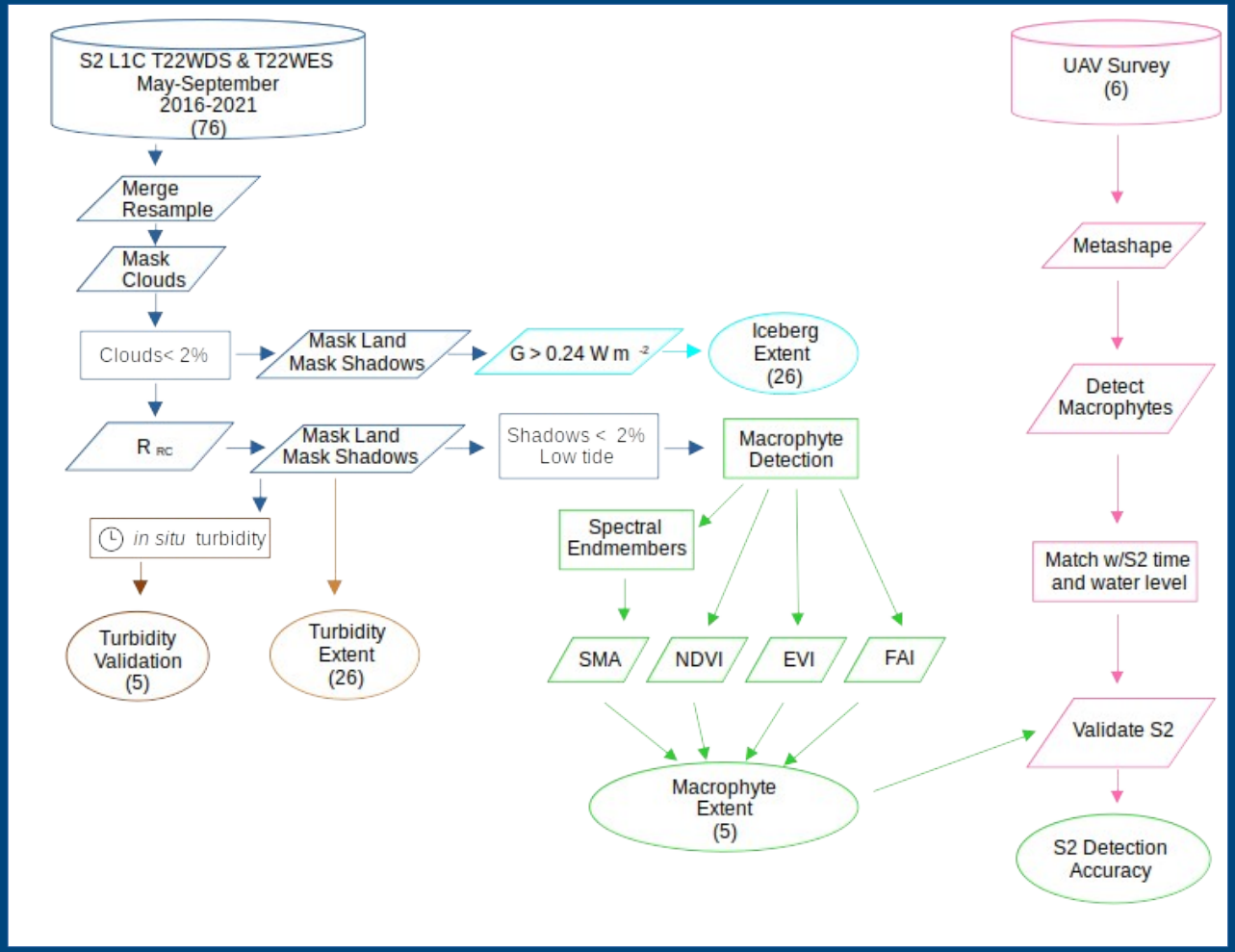
Spectral Mixture Analysis

- Classify multi-spectral imagery using representative spectra.
- Estimate sub-pixel abundance.
- Only works when sources of reflectance are spectrally distinct.

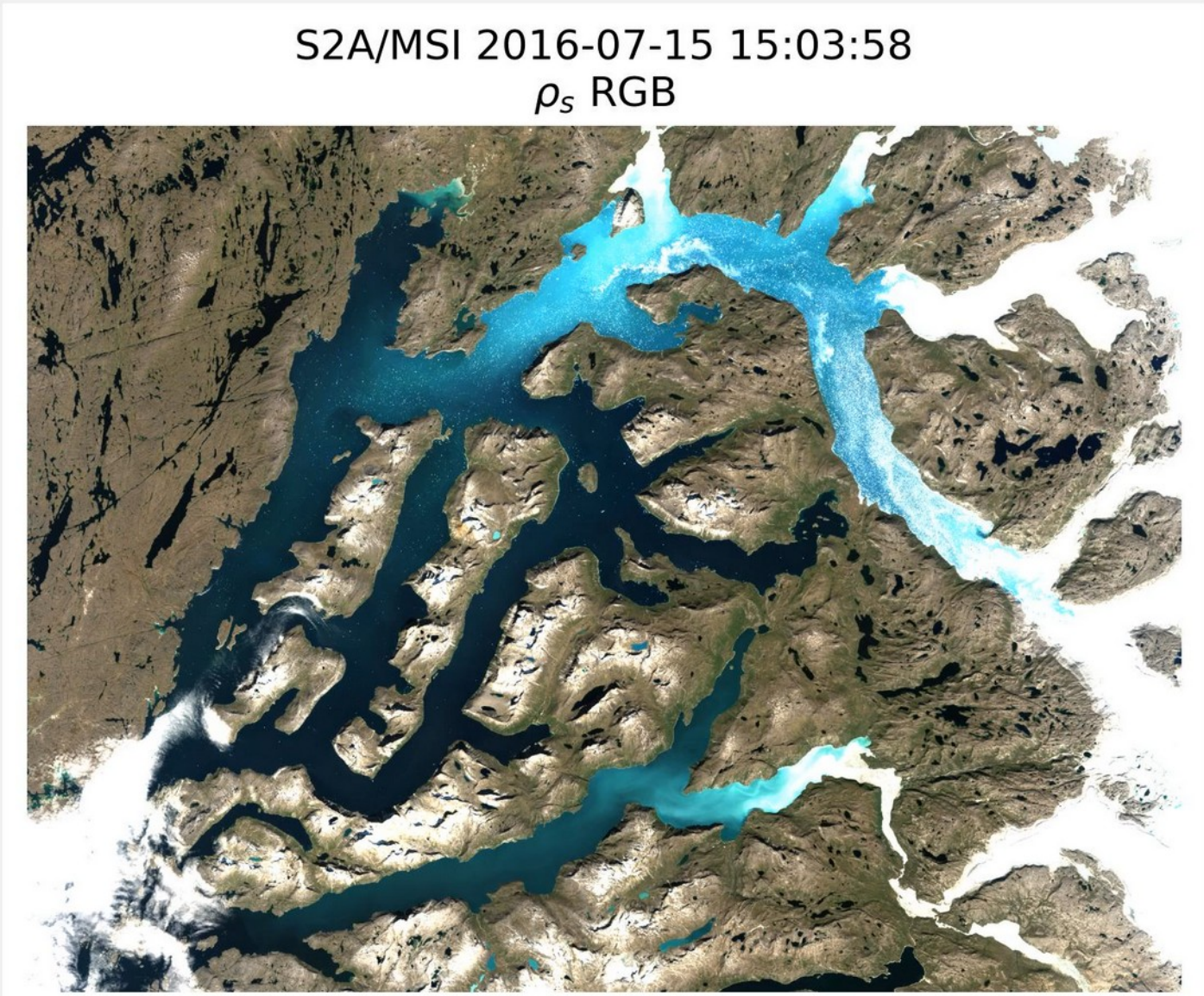


Workflow

- Cloud-free S2 images acquired between May-Sept
- Narrow window to June-July due to terrain shadows
- ACOLITE → Rayleigh-corrected reflectances
- Low tide images (and a couple high tide)
- Land mask – digital elevation model and manual
- Vegetation indices and spectral mixture analysis
- High-resolution UAV validation surveys
- Compute area of intertidal macrophyte coverage

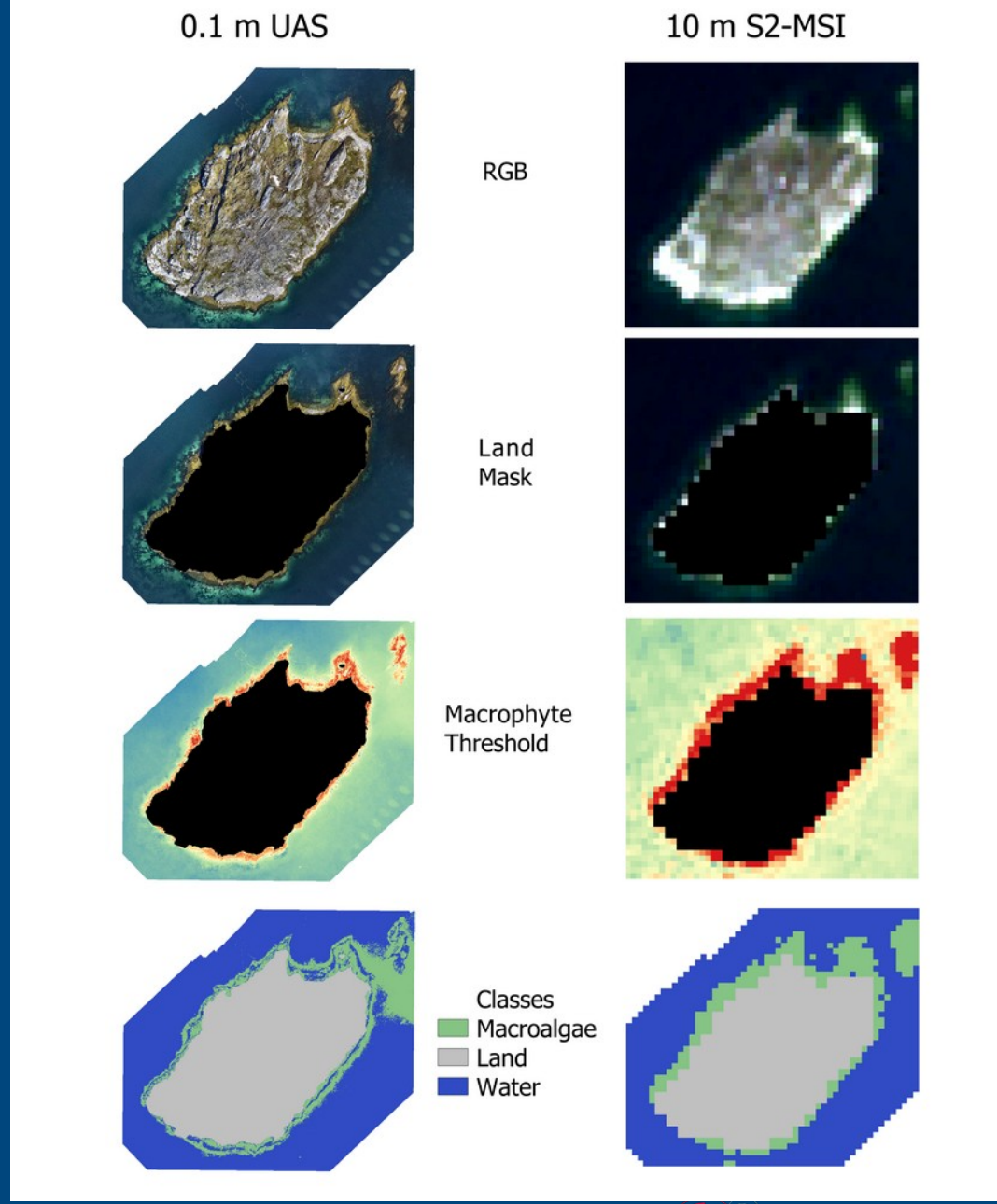


Study Area – Nuup Kangerlua and Ameralik



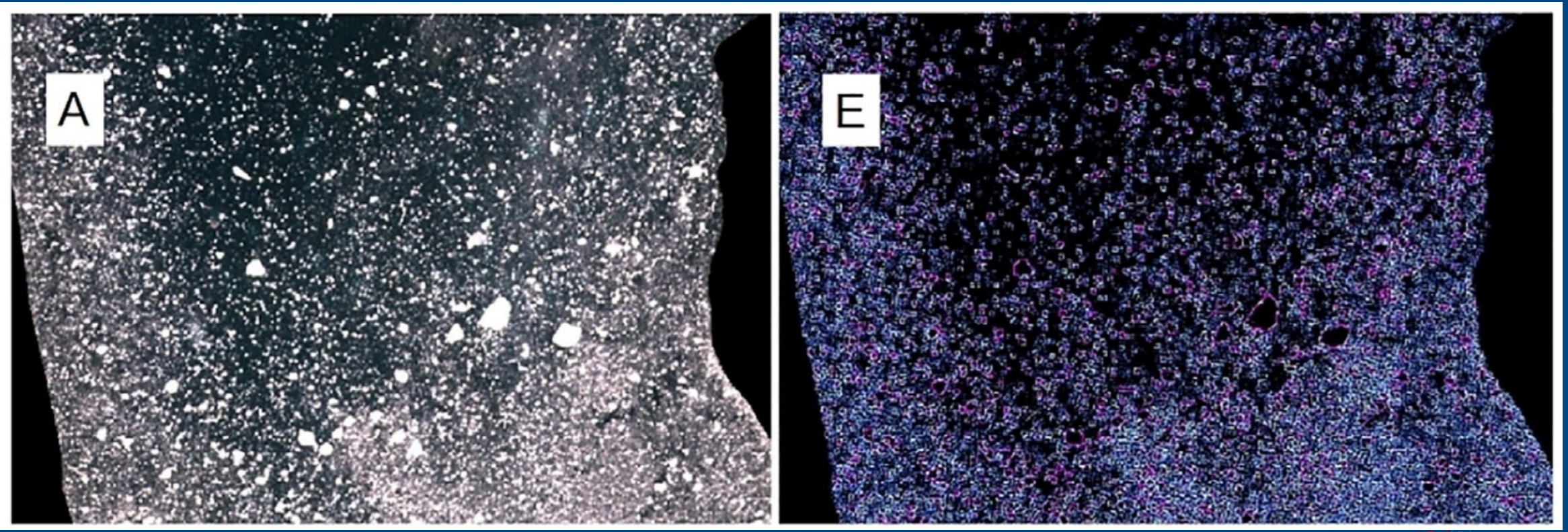
UAV Validation

- 2 UAV validation sites
- DJI Phantom 3 or Mavic
- Agisoft Metashape
- Land masked
- Macroalgae identified by applying thresholds to RGB
- Classified into land, water, macrophytes
- Validate vegetation indices and SMA



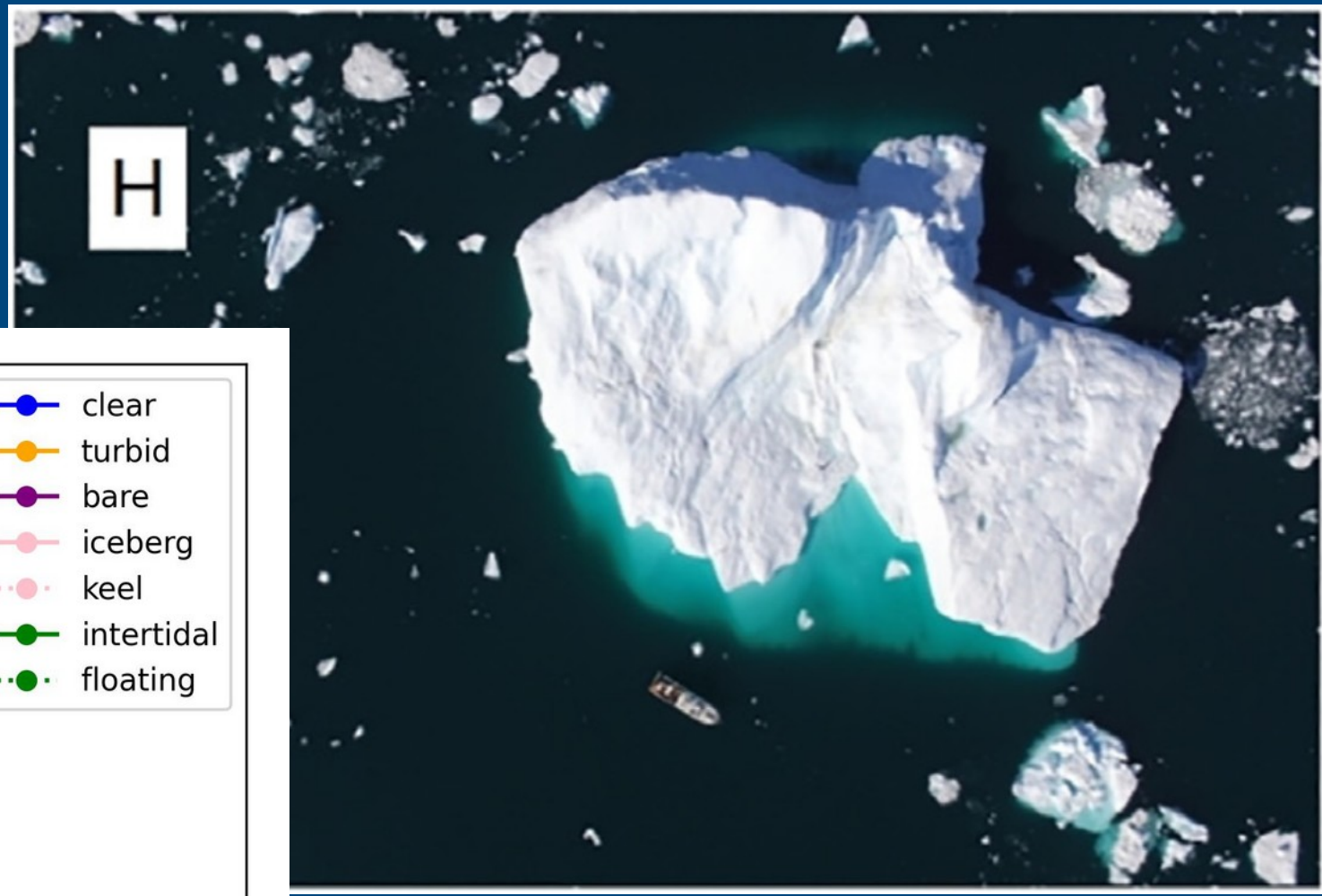
Spectral Mixture Analysis

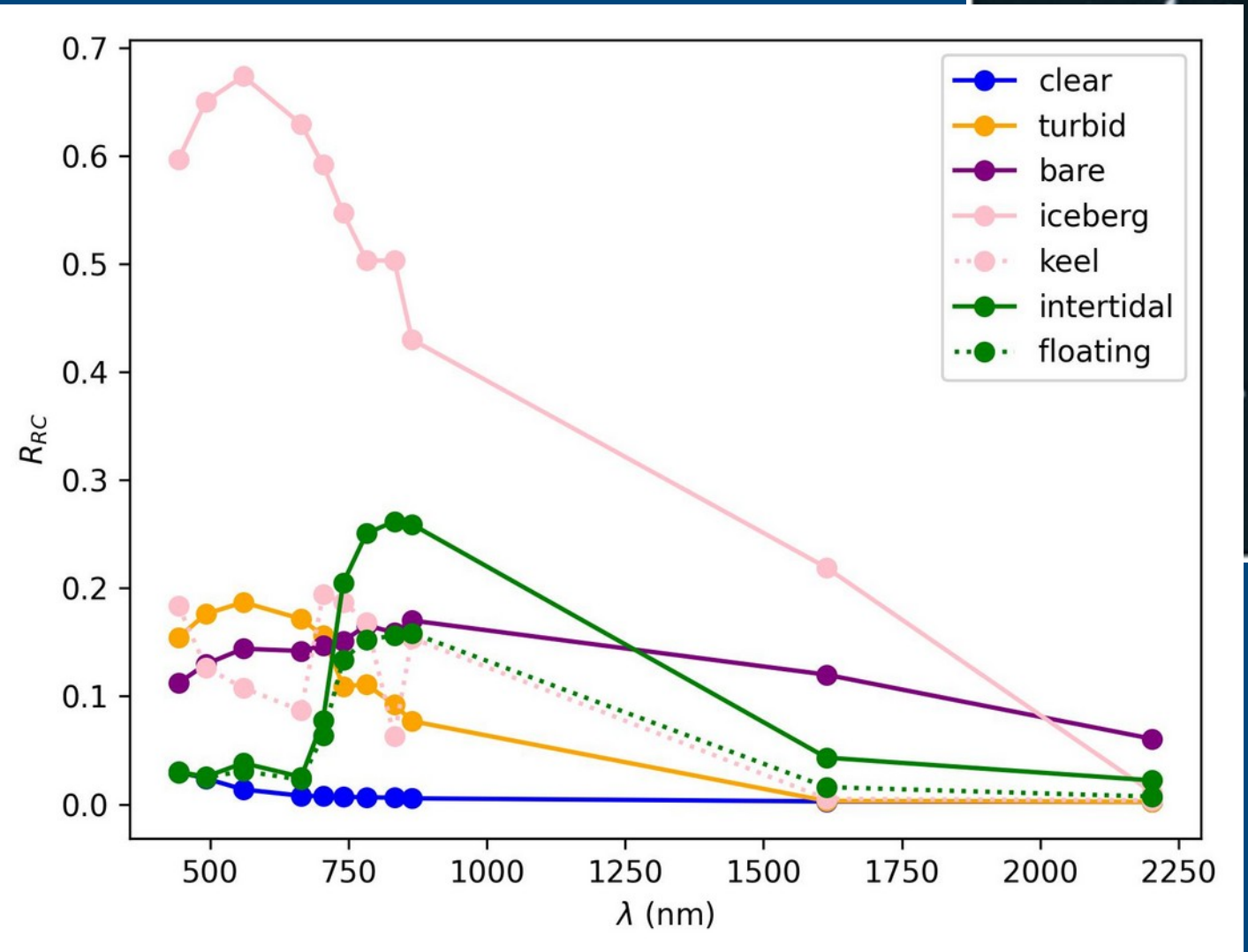
- Lowest accuracy
- Ice, mudbanks, turbidity, and macroalgae not spectrally distinct



Spectral Mixture Analysis

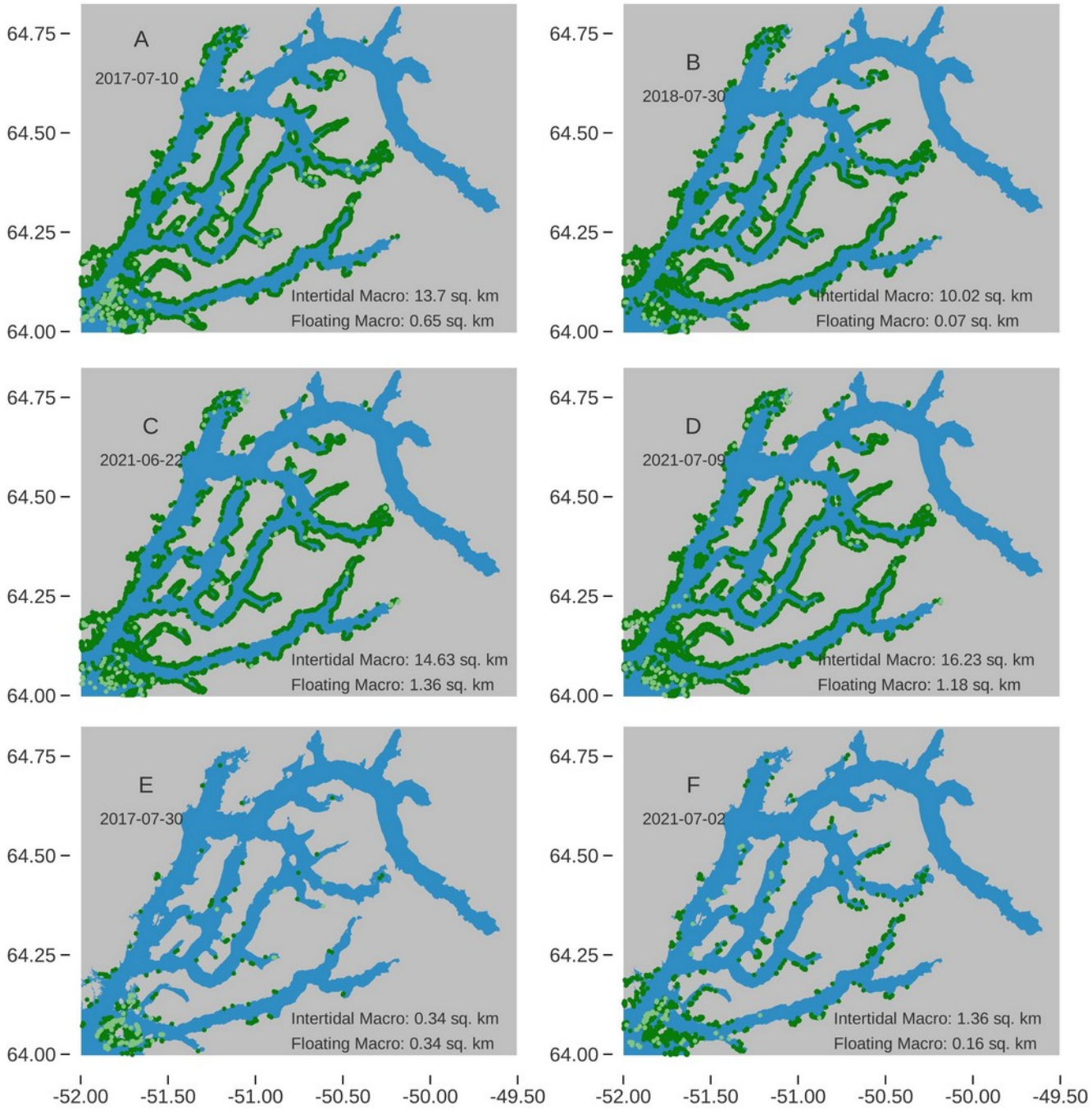
- Ice, mudbanks, turbidity, and macroalgae not spectrally distinct





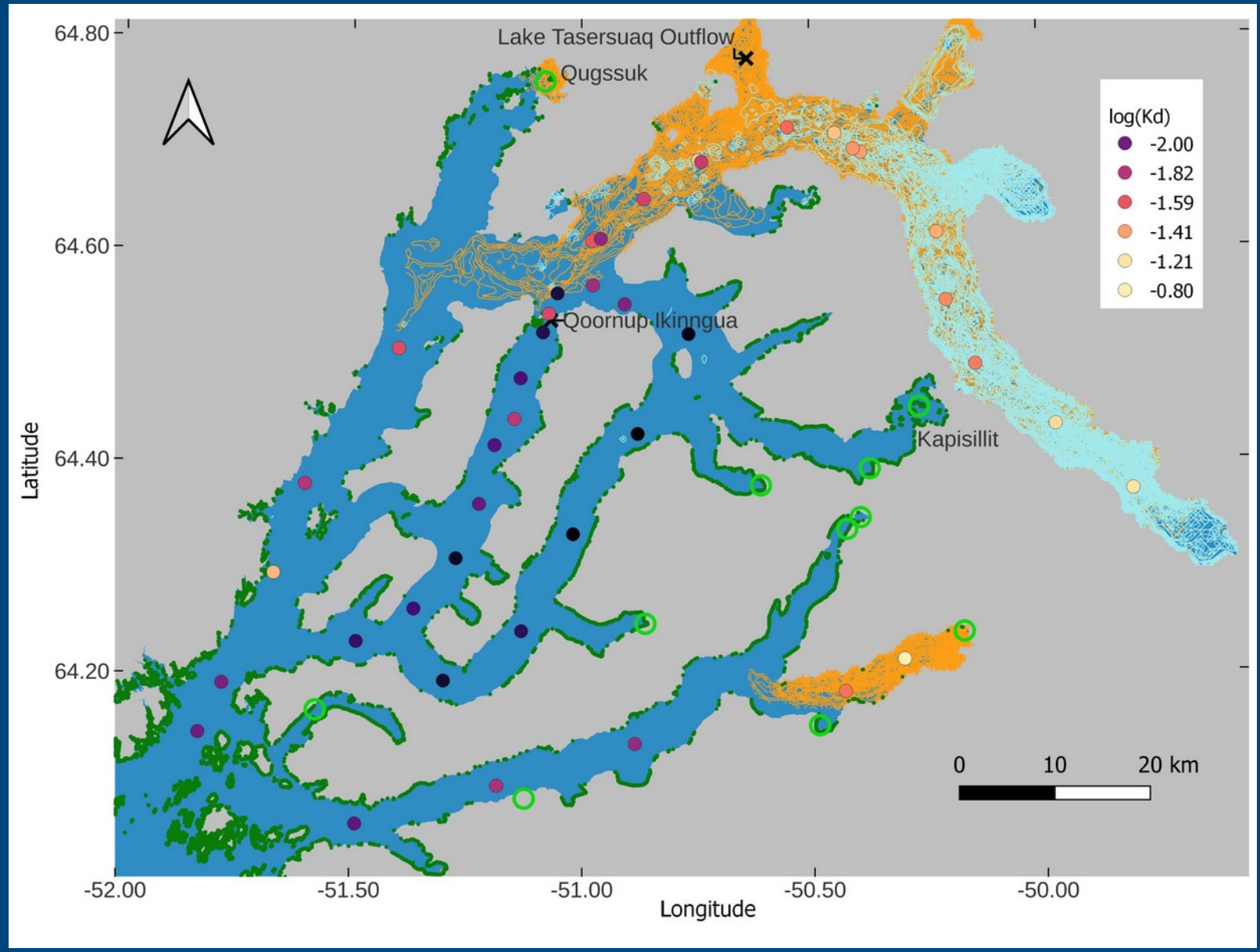
Vegetation Indices

- NDVI highest accuracy
- 4 low tide images
- Varied from 10-16 sq. km
- High tide cover: 0.34-1.4 sq. km
- Floating macroalgae visible and varied from 0.07 sq km to 1.36 sq km



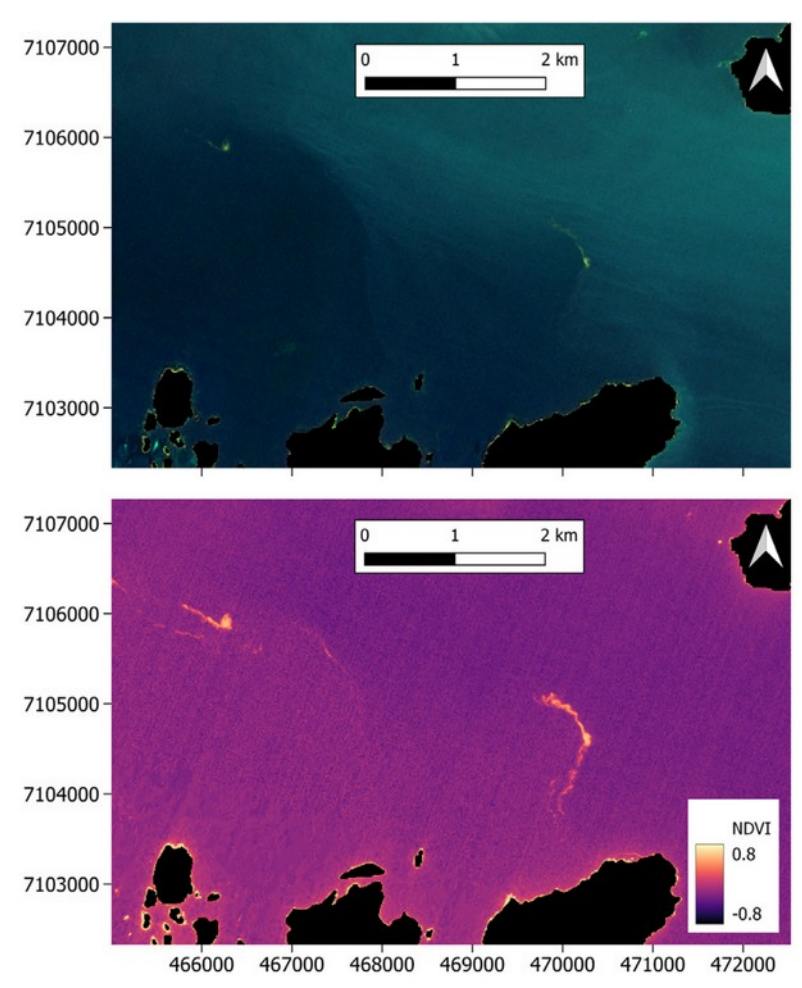
Macrophyte Distribution

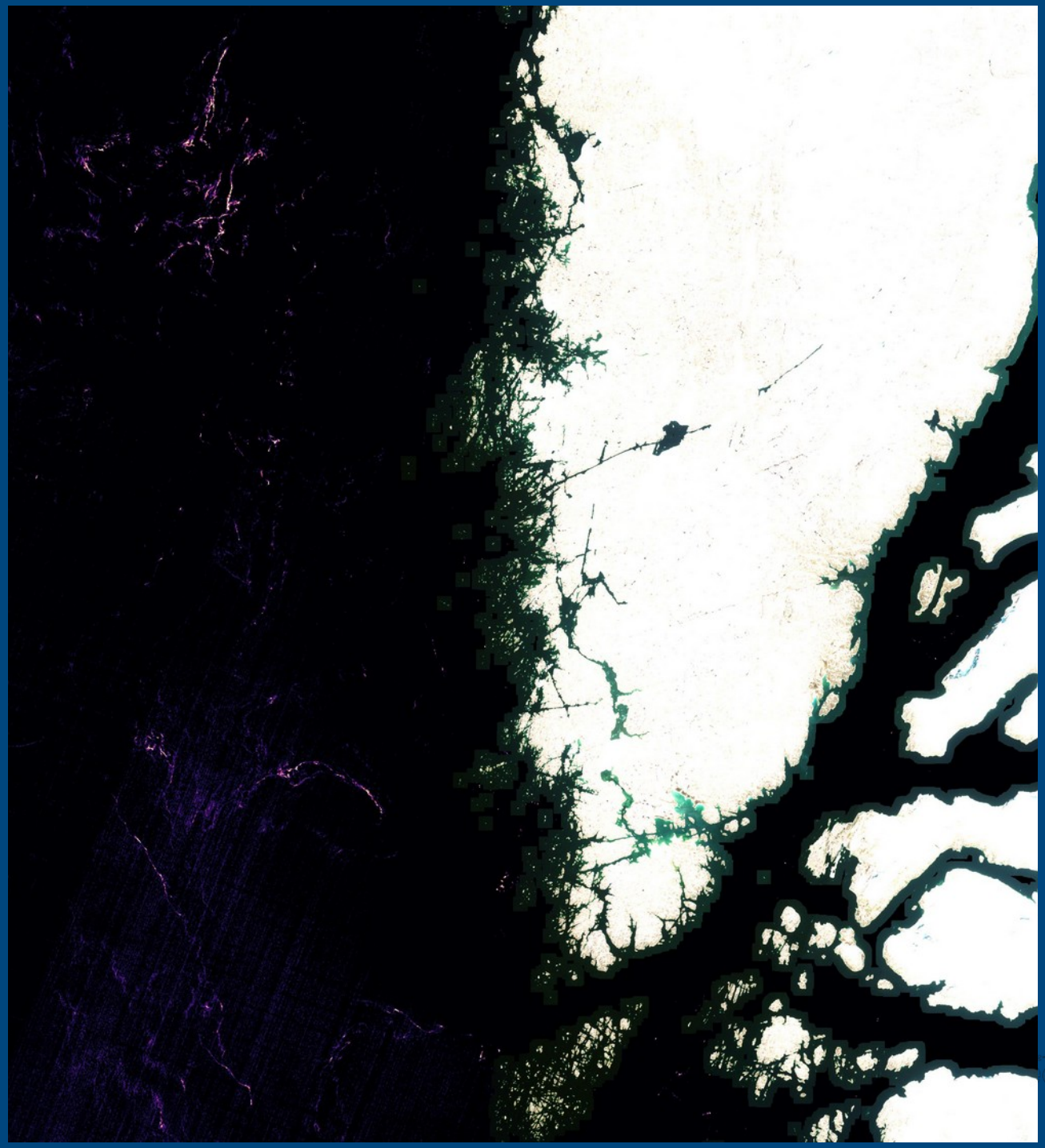
- Intertidal macrophytes detected in 3 out of 4 low tide images were retained
- Intertidal macrophytes cover 12 sq. km.
- Distribution shaped by ice and turbidity
- Retreat of marine terminating glaciers onto land may open up new coastlines for macroalgal colonization



Floating Macroalgae

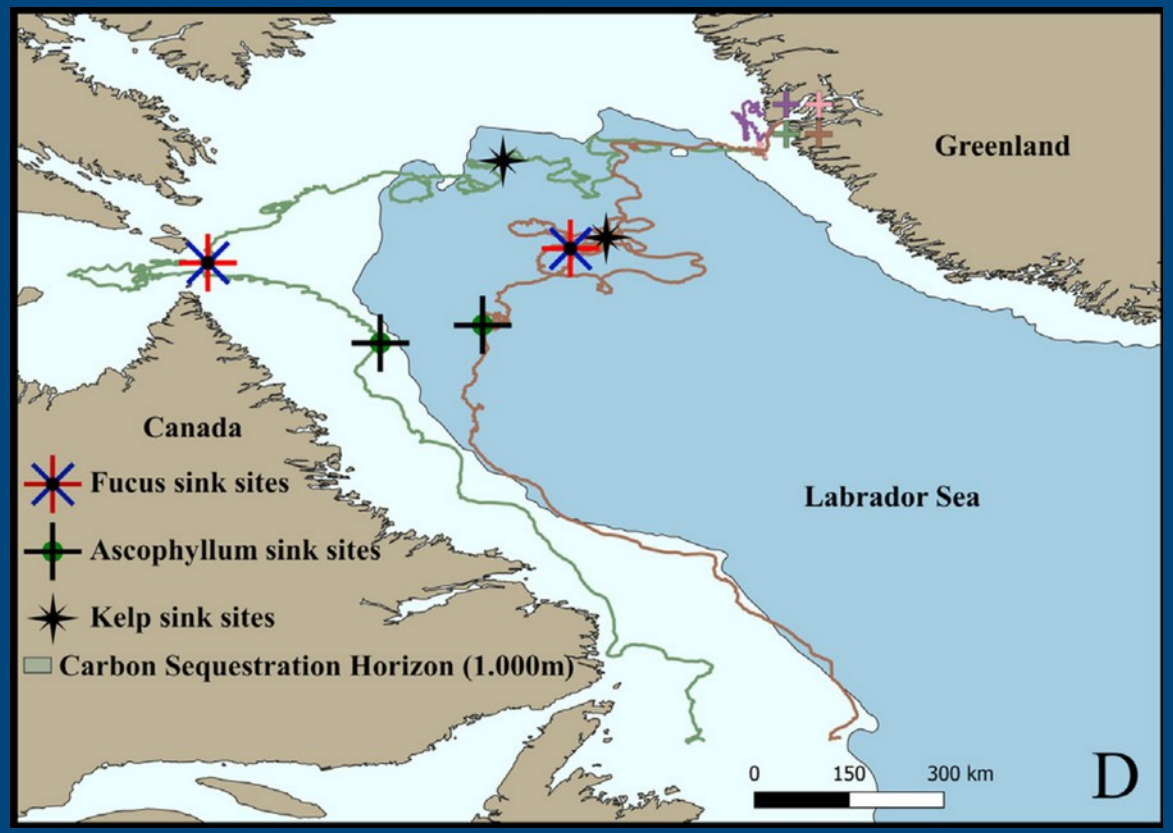
- Highly variable
- Most abundant near the mouth of the fjord and on the shelf
- Large mats visible in RGB





Floating macroalgae in Nuup Kangerlua

- Field sampling of floating macroalgae from April-August 2021
- Sentinel-2 and WorldView-3
- GPS-tracked surface drifters



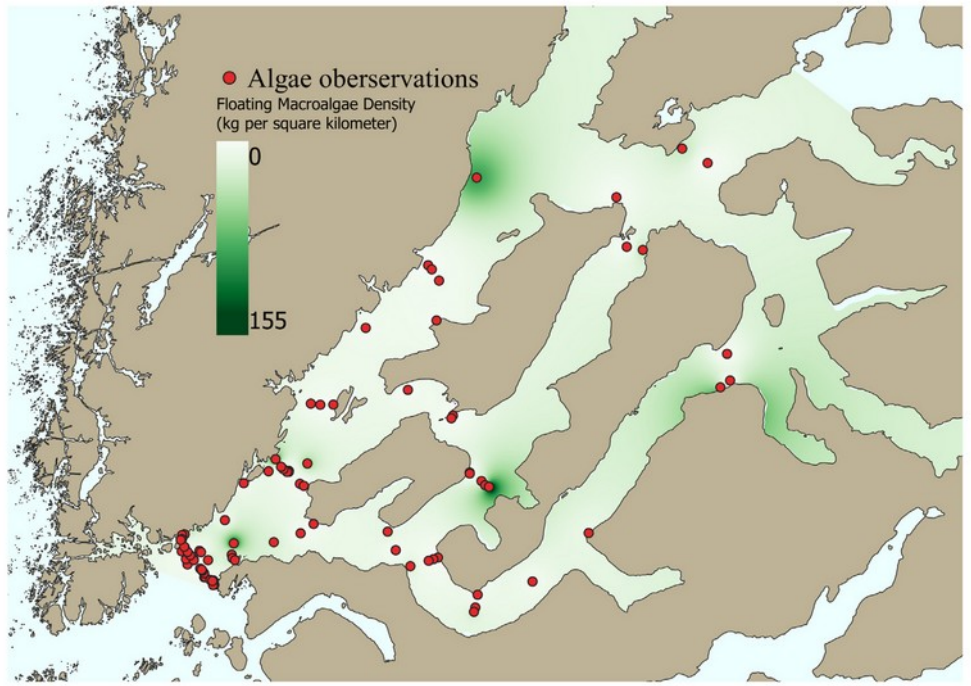
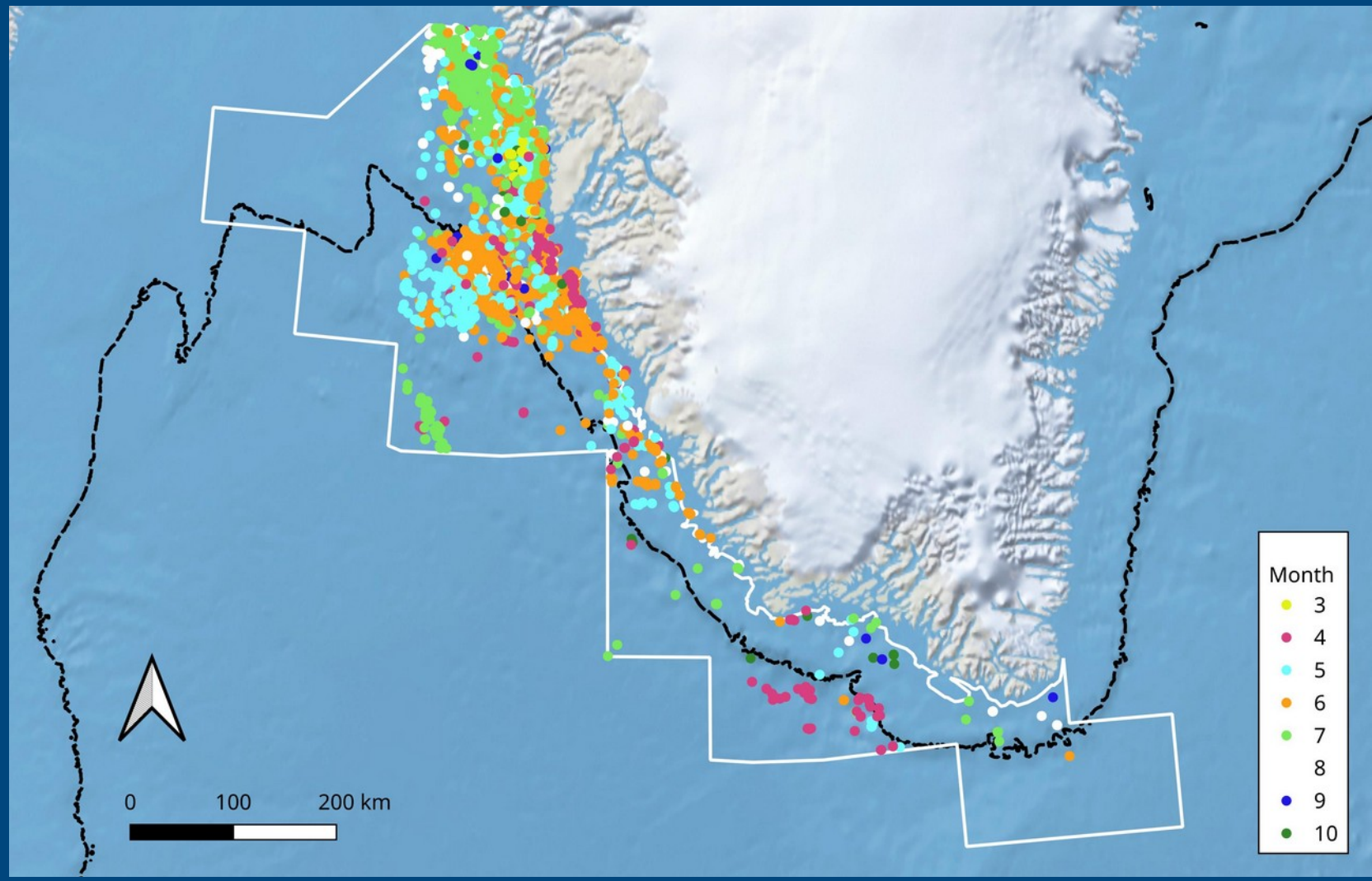


Fig. 3. Floating macroalgal densities in Nuup Kangerlua.
Contours indicate interpolated floating macroalgal density estimated from macroalgal observations in April, June, and August 2021.

Offshore Export and Sinking - Ongoing

- Sentinel-2 imagery of the entire SW Greenland shelf
- 24 S2 Tiles
- March – October; 2016-2024
- 1350 images analyzed
- Clearly demonstrates widespread presence of floating macroalgae on the shelf and beyond the shelf break
- Oceanographic connectivity assessed with surface drifters and Lagrangian particle tracking
- Role of deep convective mixing examined using Large Eddy Simulation



Thank you!

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