Remote detection of marine debris using vis-NIR satellite observations: challenges and potentials

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Outline

1. Background
2. Why is it so difficult?
3. What can be done?

1. Background

Marine debris refers to any persistent solid material that is disposed of (or abandoned) in the marine environment by natural processes (including natural disasters such as Tsunami) and human activities, for example microplastic particles, plastic bags or bottles, cigarette butts, foam take-out containers, balloons, fishing gear, tree branches/leaves, wood, among others.

Every year, at least 8 million tons of plastic materials enter the ocean, causing various environmental problems. Some of these are broken into microplastic peaces (< 5 mm), which can be ingested by animals and enter the food chain.

Marine litter off Honduras (Cozar et al., 2021).
Photo credit: C. Power

1. Background

Macroplastics and microplastics collected from the N Atlantic (Garaba & Dierssen, 2018)

1.68 mm – 2.00 mm

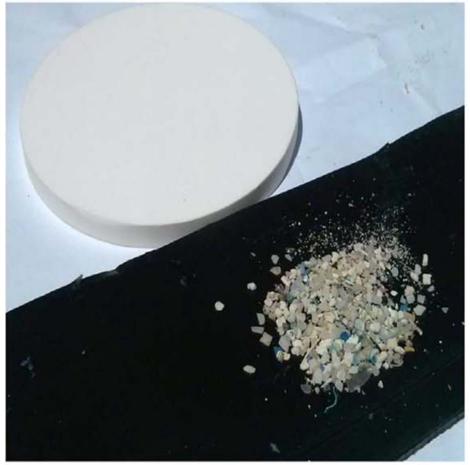
2.00 mm – 2.38 mm

2.38 mm – 2.83 mm

2.83 mm – 3.36 mm

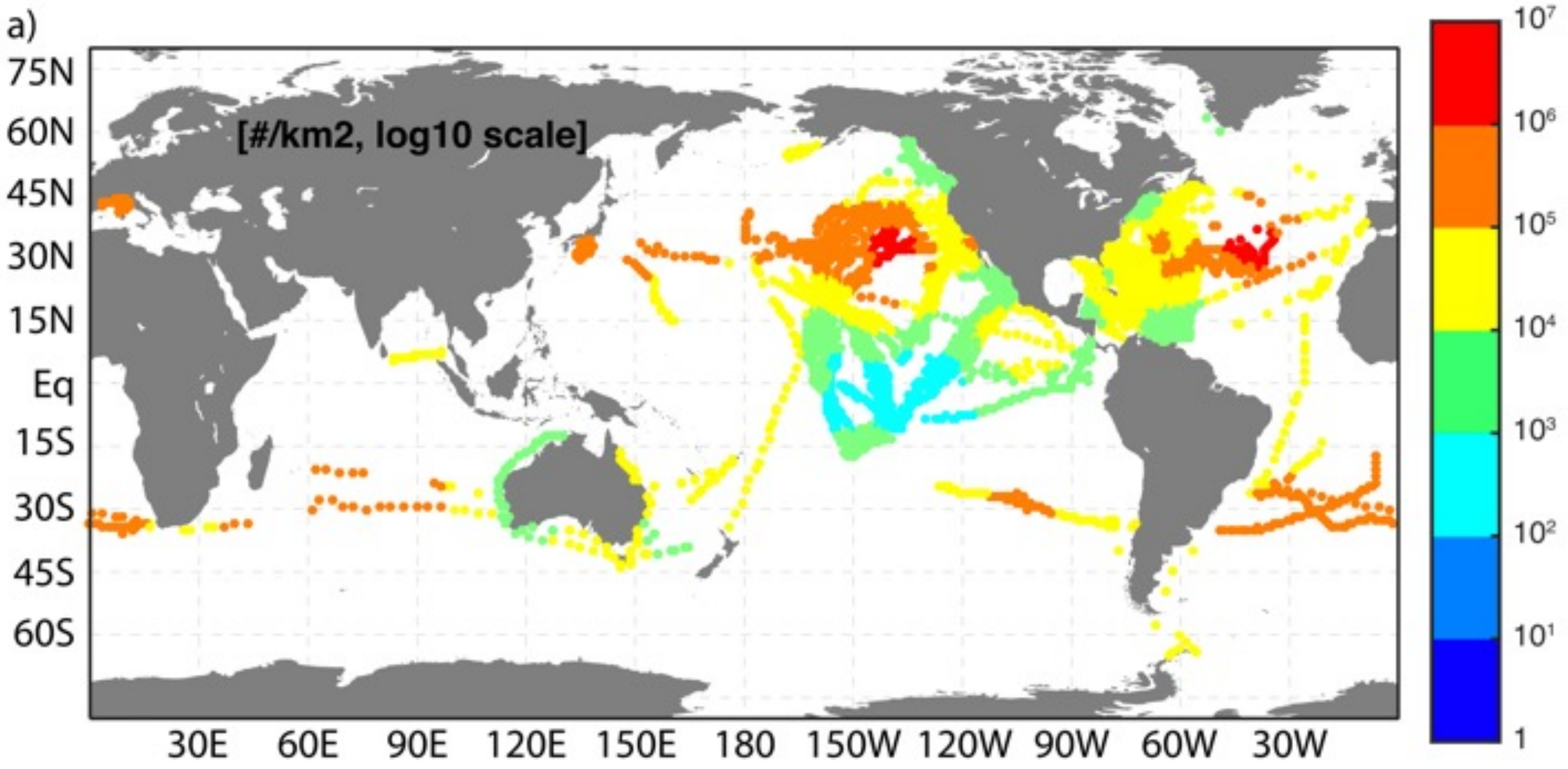
3.36 mm – 4.00 mm

Sampling setup



1. Background

11,854 surface trawls from 1971 – 2013 (van Sebille et al., 2015)



Maximum microplastics density: 10 M pieces/km^2

Question: Can we detect and monitor these various forms of marine debris from space? How?

There are some papers to show the possibility, based on either controlled experiments or satellite images. However, these are the first attempts, and I want to show why it is so difficult and what may be possible now and in the near future – with the focus on vis-NIR remote sensing.

Technical steps in remote sensing of floating matters

I. Is there “something”?

II. What is that?

III. How much?

Technical steps in remote sensing of floating matters

I. Is there "something"?

$$\Delta R = R_{target} - R_w = [\chi R_{\mathrm{FM}} + (1- \chi)R_{\mathrm{W}}] - R_w = \chi(R_{\mathrm{FM}} - R_{\mathrm{W}})$$

To be able to see "something" in an image, we need

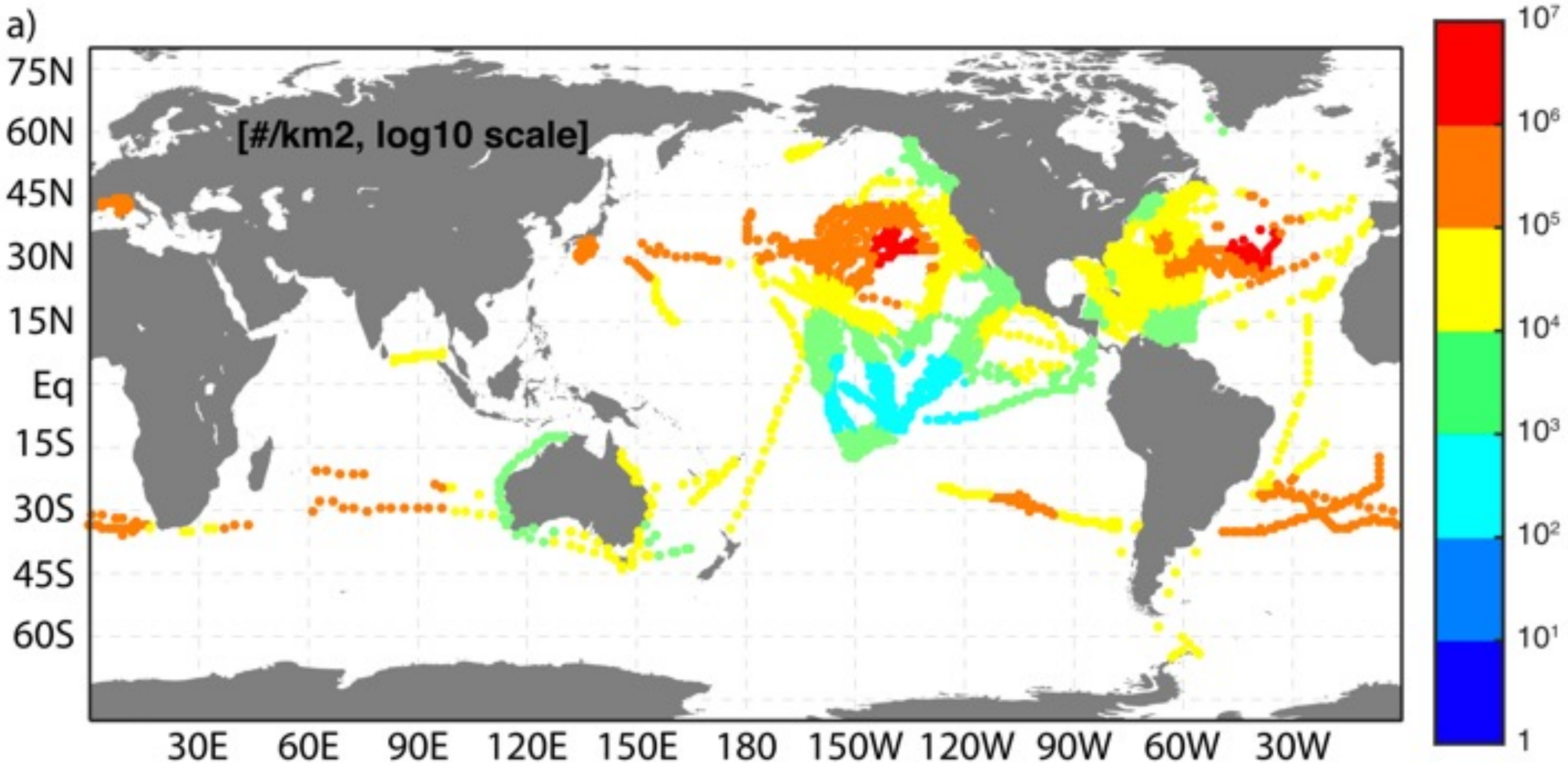
$$\Delta R > 2\sqrt{2}\sigma \quad => \quad \chi_{\mathrm{det}} \geq 2\sqrt{2}\sigma \,/\, \max(R_{\mathrm{FM}} - R_{\mathrm{W}})$$

ΔR:	reflectance difference between target and water pixels
σ:	sensor noise;
R_{FM}:	reflectance of floating matter;
R_w:	reflectance of water;
χ:	sub-pixel coverage of floating matter (0% - 100%)
χ_{det}:	sub-pixel detection limit

Assuming $\max(R_{\mathrm{FM}} - R_{\mathrm{W}}) = 0.3$, SNR = 200: $\chi_{\mathrm{det}} \approx 0.2\%$; For MSI: $\chi_{\mathrm{det}} \approx 0.8\%$

Qi and Hu (2021)

Can microplastics be detected?

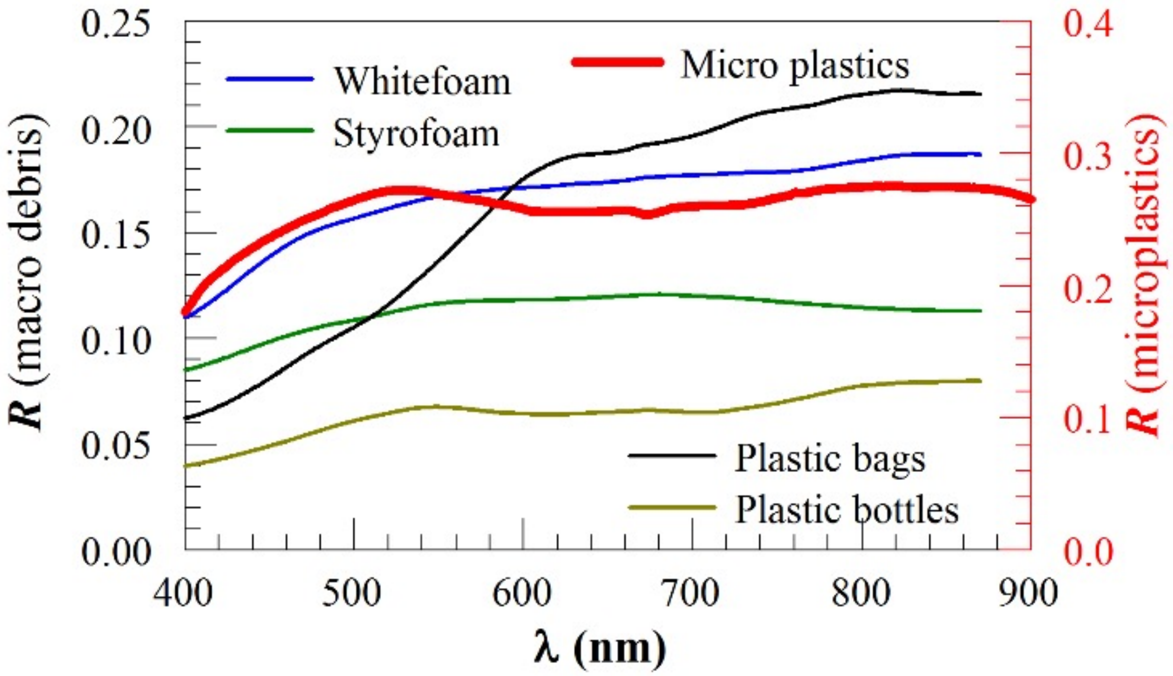


Maximum: 10 million particles/km^2, or 10 particles/m^2, or $\chi \approx 0.005\%$ assuming mean particle size of 2.5 mm

Technical steps in remote sensing of floating matters

II. What is that "something"?

Spectral characteristics and spectral discrimination



Experiment in Tampa Bay (Hu et al., 2015; Hu, 2021)
Microplastic spectra from Garaba and Dierssen (2020)

Technical steps in remote sensing of floating matters

II. What is that "something"?

Spectral characteristics and spectral discrimination

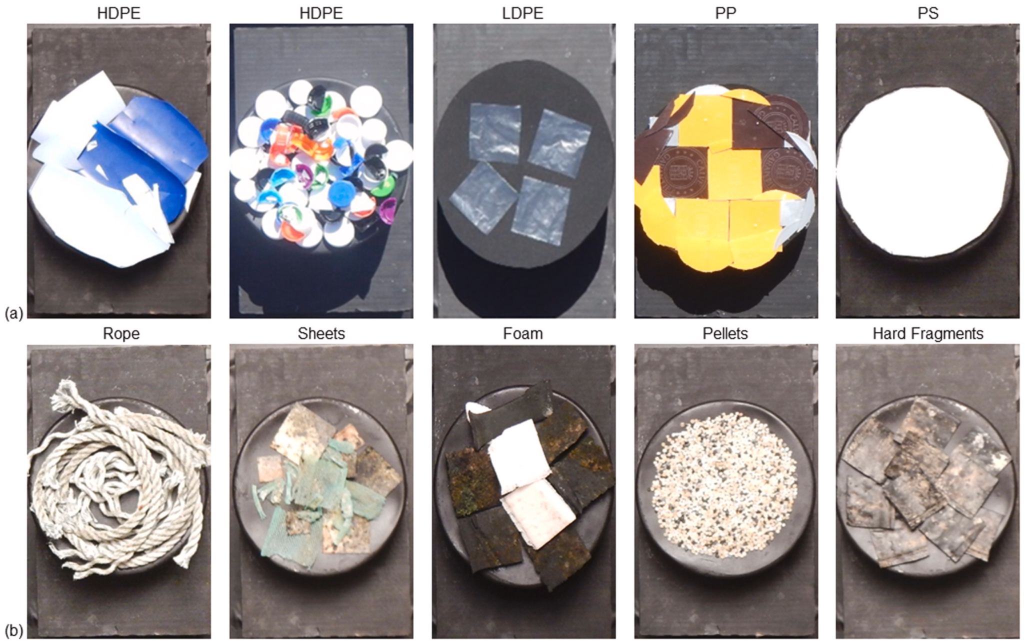
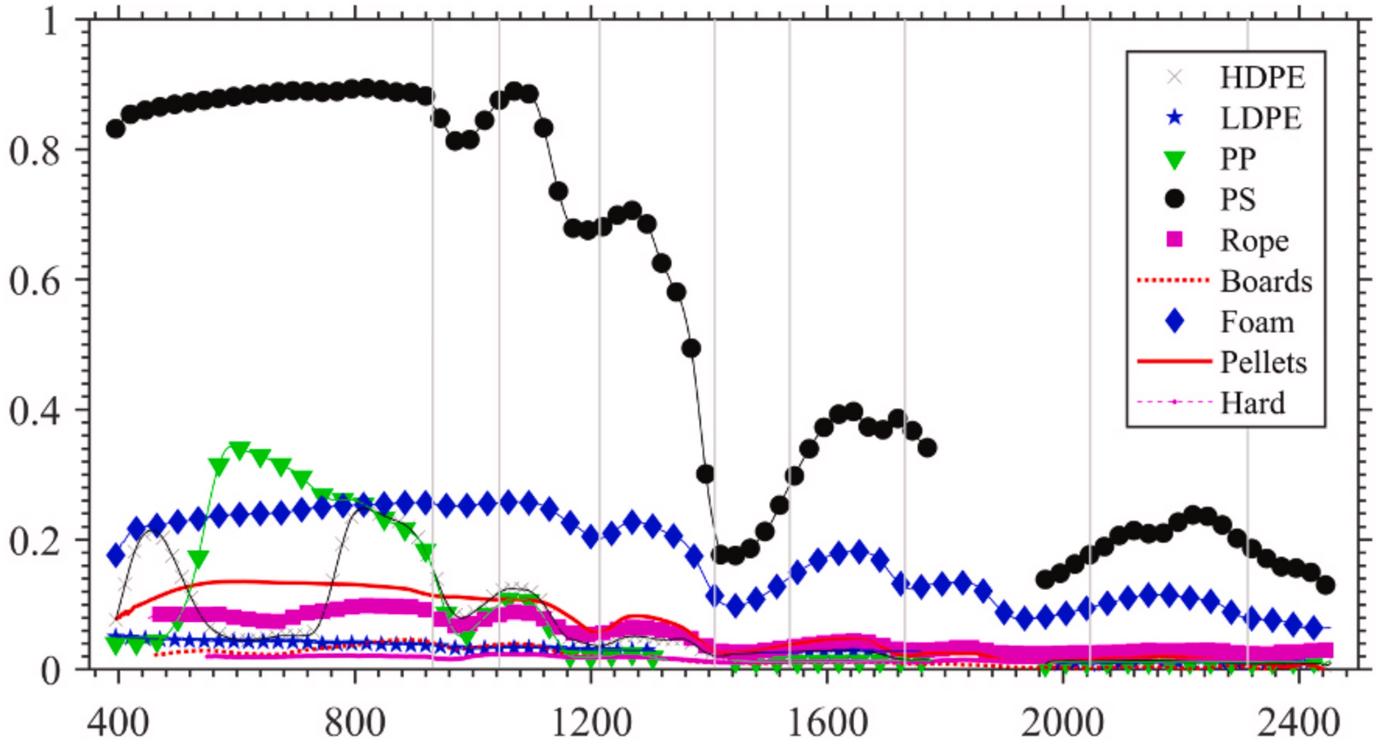


Fig. 1. (a) Virgin samples of high and low density polyethylene (HDPE, LDPE), polypropylene (PP), polystyrene (PS) representative of polymers common in ocean floating plastic litter and (b) rope, sheets, foam, pellets and fragmented items harvested from the North Pacific Garbage Patch between 27 July and 19 September 2015 (Lebreton et al., 2018).

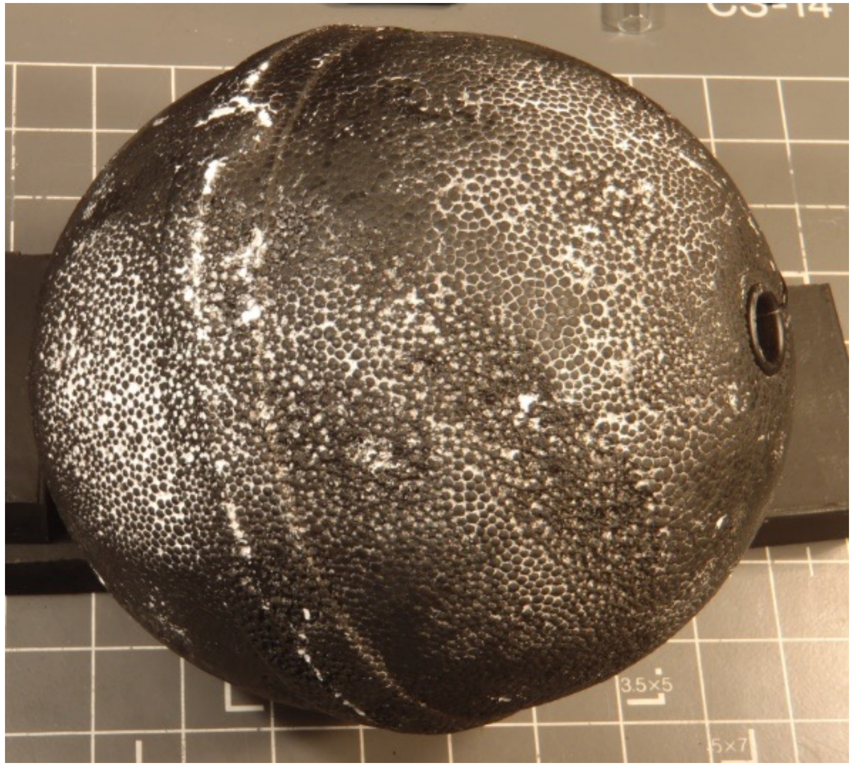


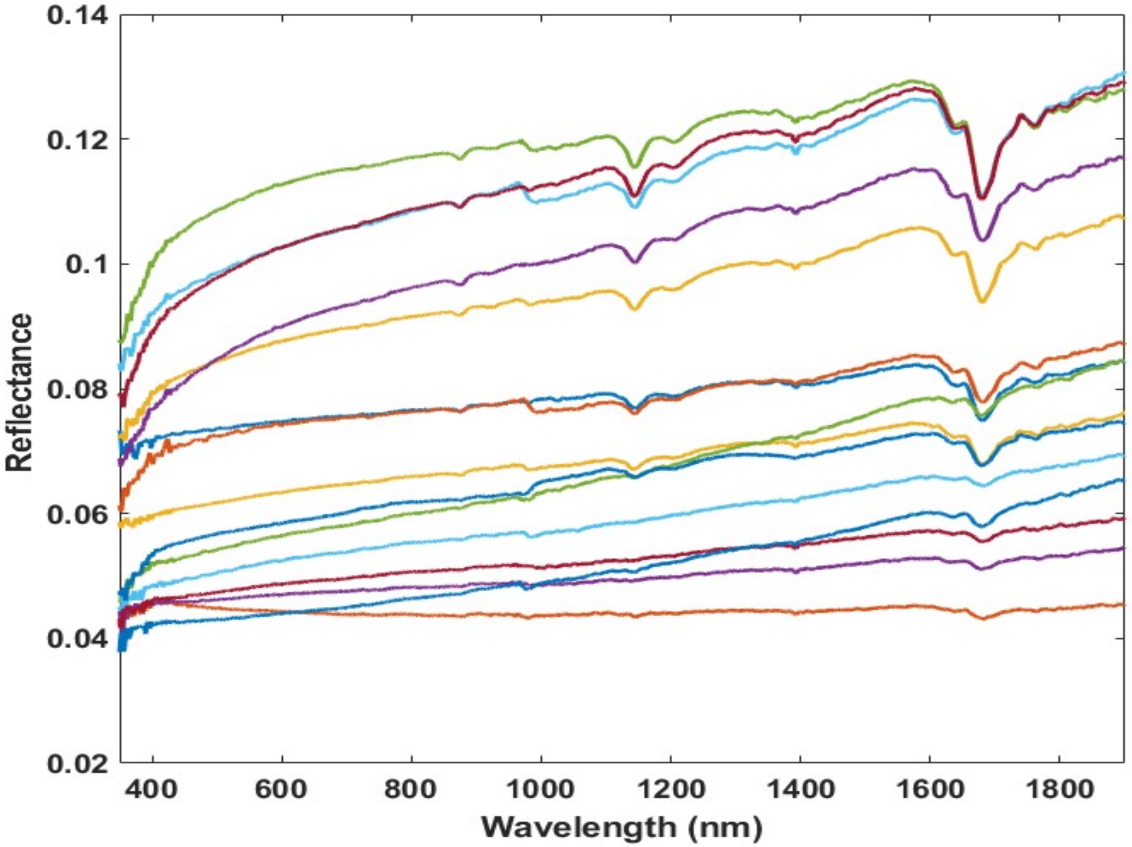
Laboratory experiment of virgin and ocean-harvested plastics (Garaba et al., 2021)

Technical steps in remote sensing of floating matters

II. What is that "something"?

Spectral characteristics and spectral discrimination



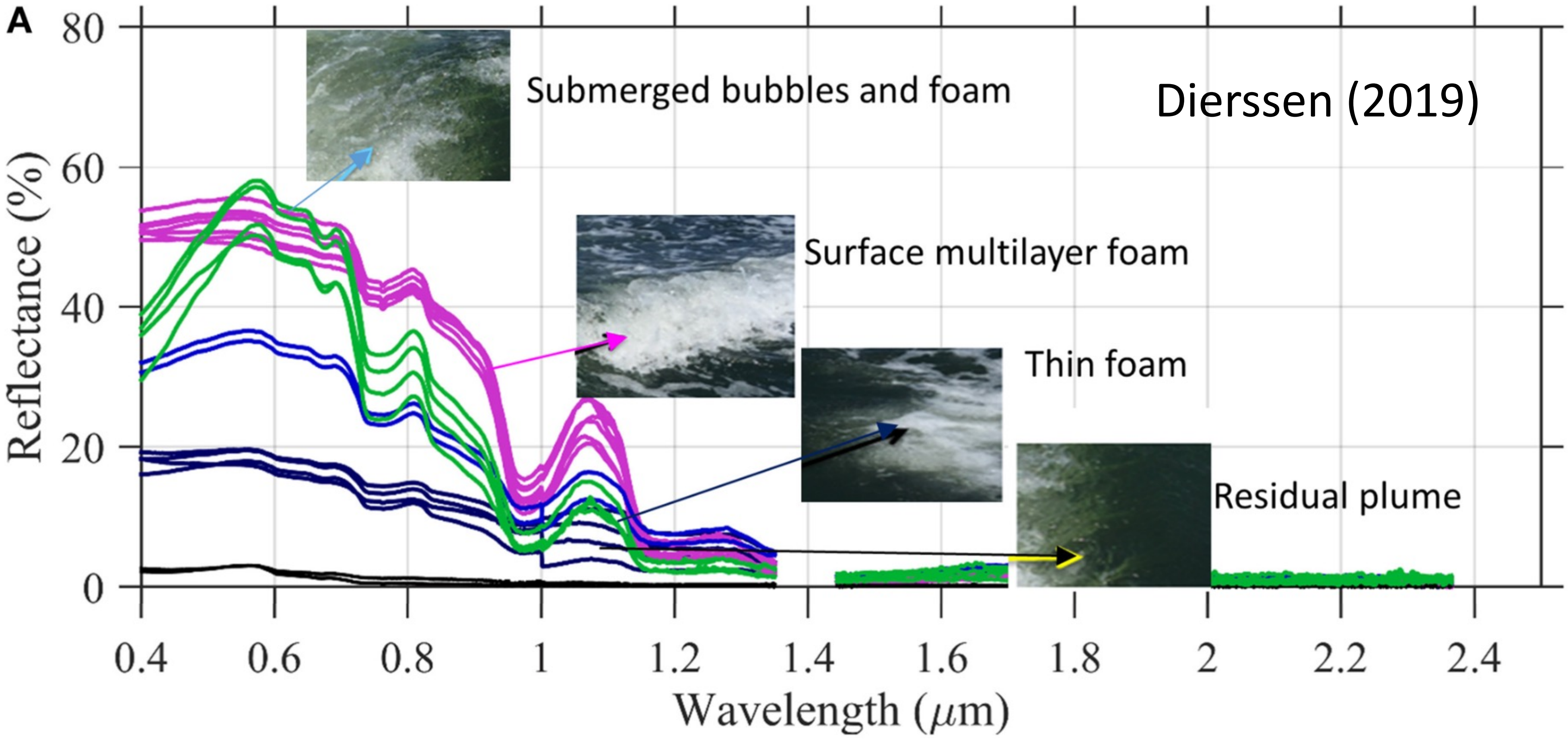


Lightly weathered black fishing trap float (~19 cm), and reflectance of different parts of the float (FOV < 4 cm) (David English, USF experiment, 2021)

Technical steps in remote sensing of floating matters

II. What is that "something"?

Spectral characteristics and spectral discrimination



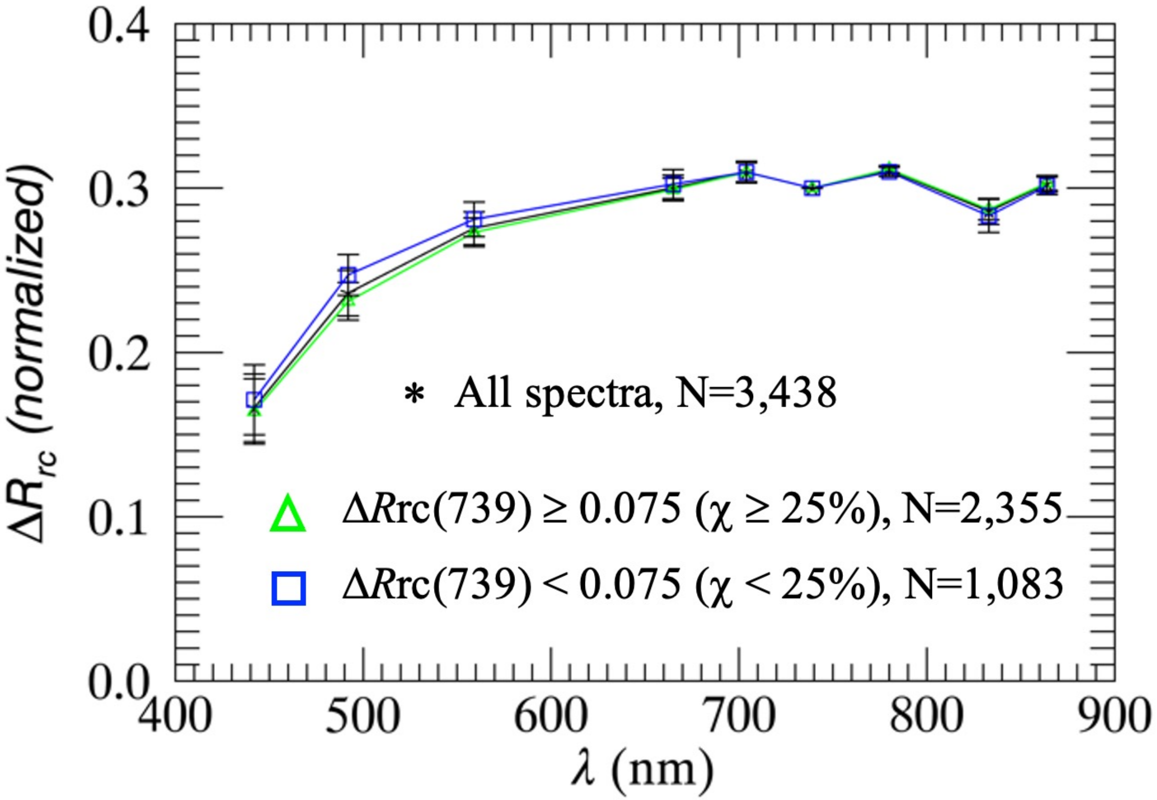
Technical steps in remote sensing of floating matters

II. What is that "something"?

Spectral characteristics and spectral discrimination

Sea snot, Marmara Sea, 2 May 2021
(photo credit: AP)

Sample spectra, Sentinel-2
(Hu et al., unver review)

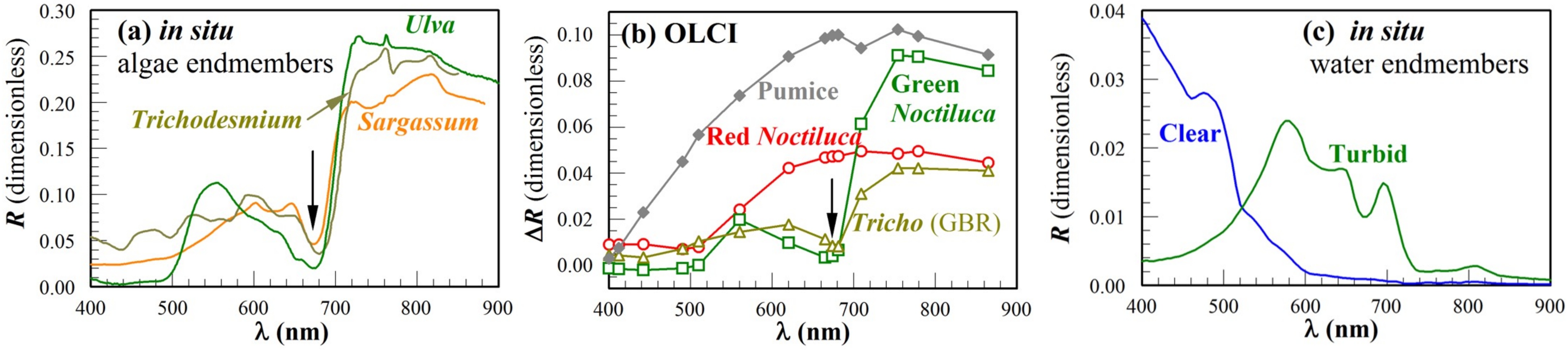


Technical steps in remote sensing of floating matters

II. What is that "something"?

Spectral characteristics and spectral discrimination

Many other types of floating matters



Hu (2021)

Technical steps in remote sensing of floating matters

III. How much is that "something"?

Spectral unmixing – size matters!

Marine debris paches are smaller than the pixel size of nearl all optical remote sensors, including the popular Sentinel-2 sensors (10 – 20 m). Unmixing a mixed pixel is doable, but not straightforward due to variable water background

2. Why is it so difficult?

- Too small – difficult to detect a spatial anomaly
- Too many types of floating matters – difficult to discriminate spectrally
- Too small – difficult to unmix a pixel

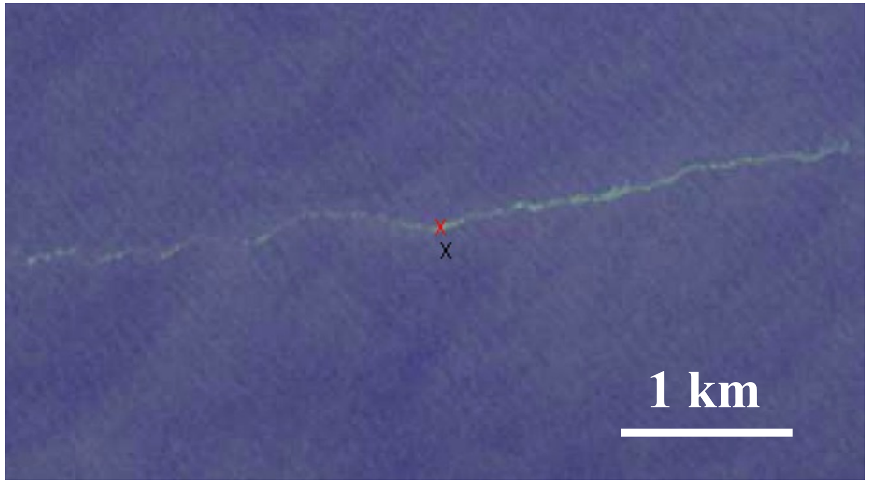
3. What can be done?

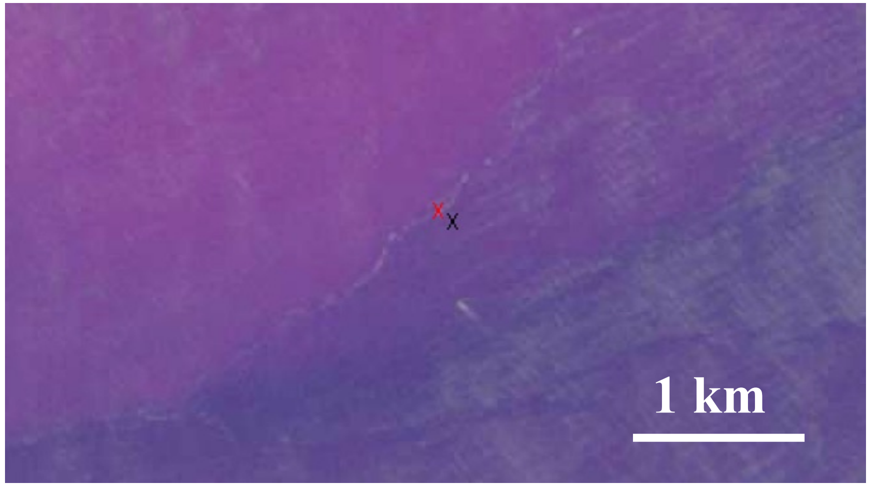
First: spatial anomaly

SW Caribbean Sea,

Nov 29, 2015

Sentinel-2

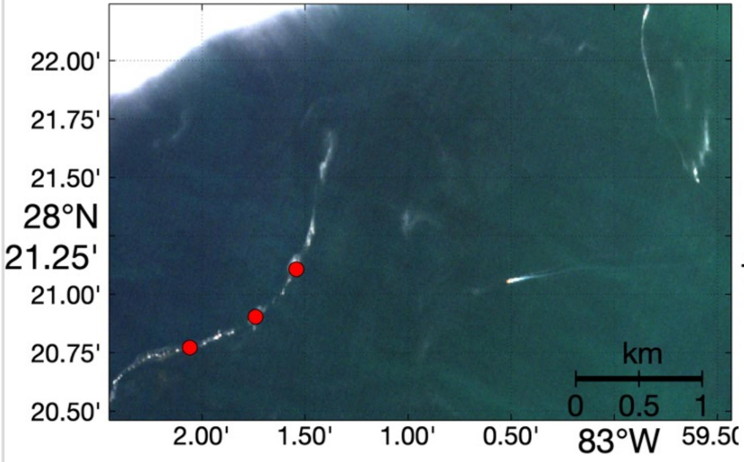


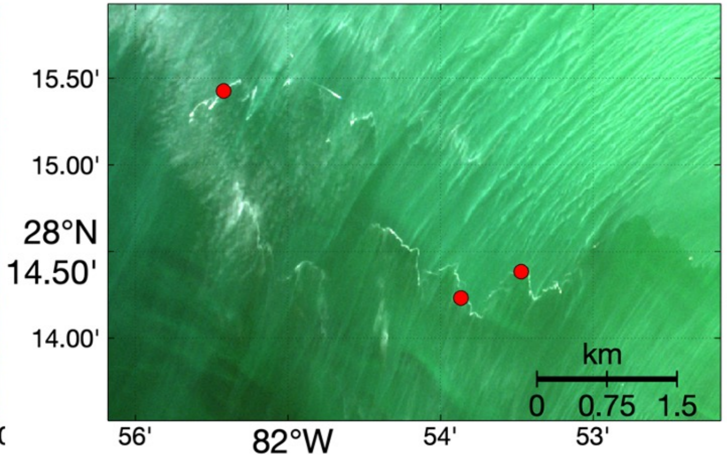


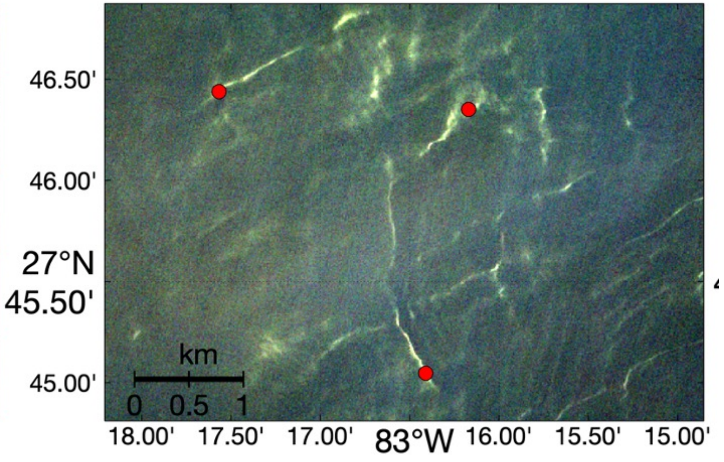
Florida Shelf,

Feb 10, 2021

Sentinel-2



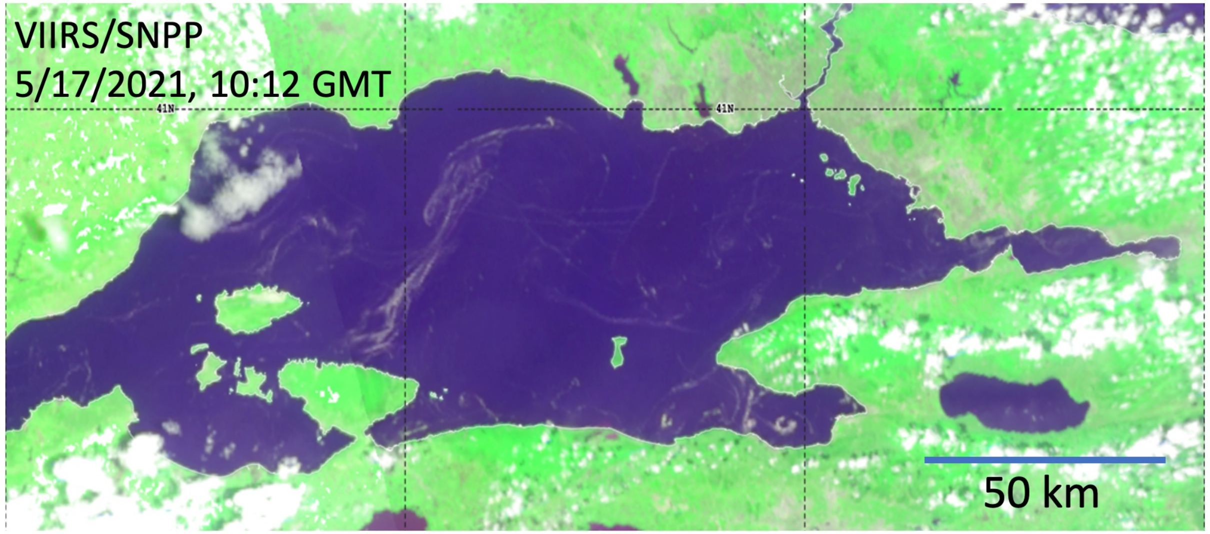


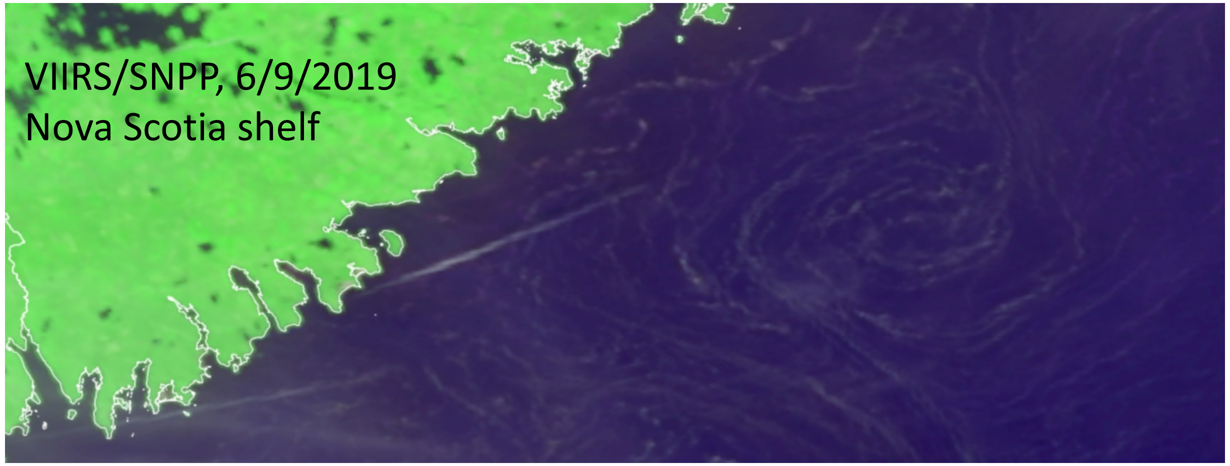


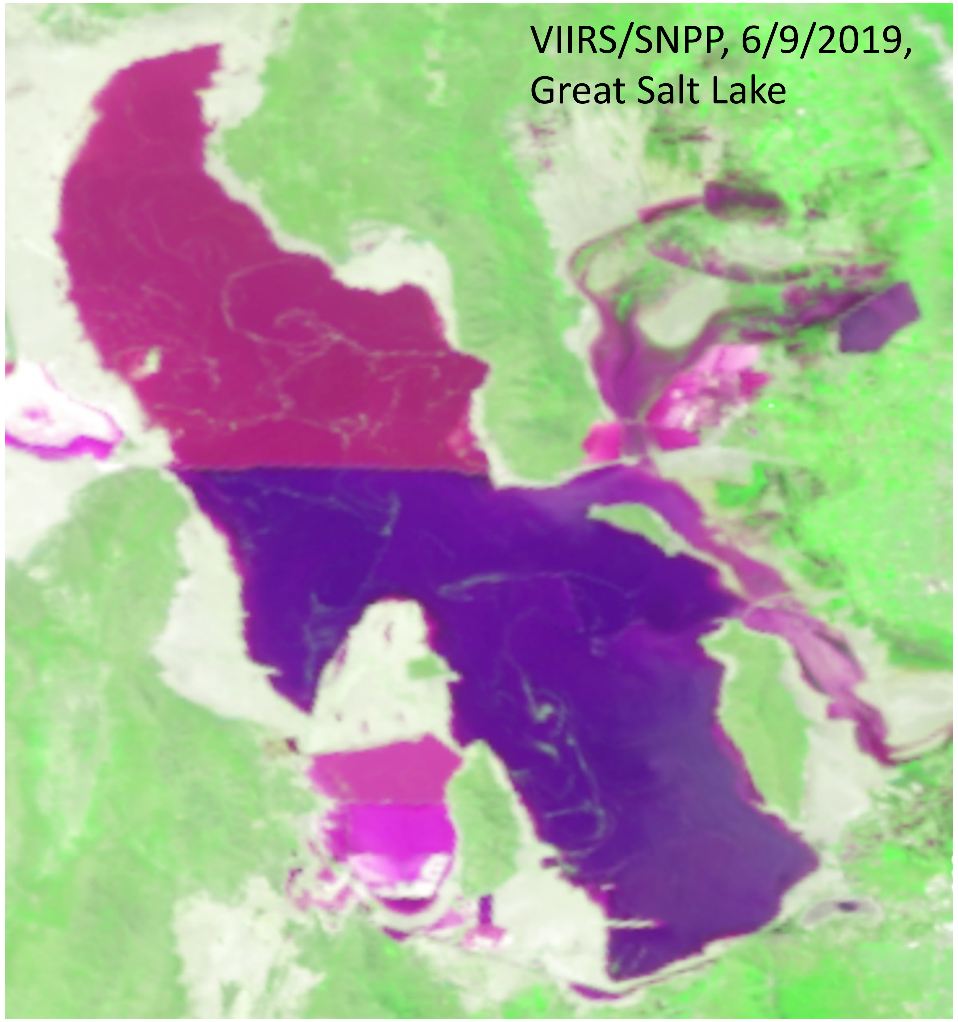
Hu (2021)

3. What can be done?

First: spatial anomaly







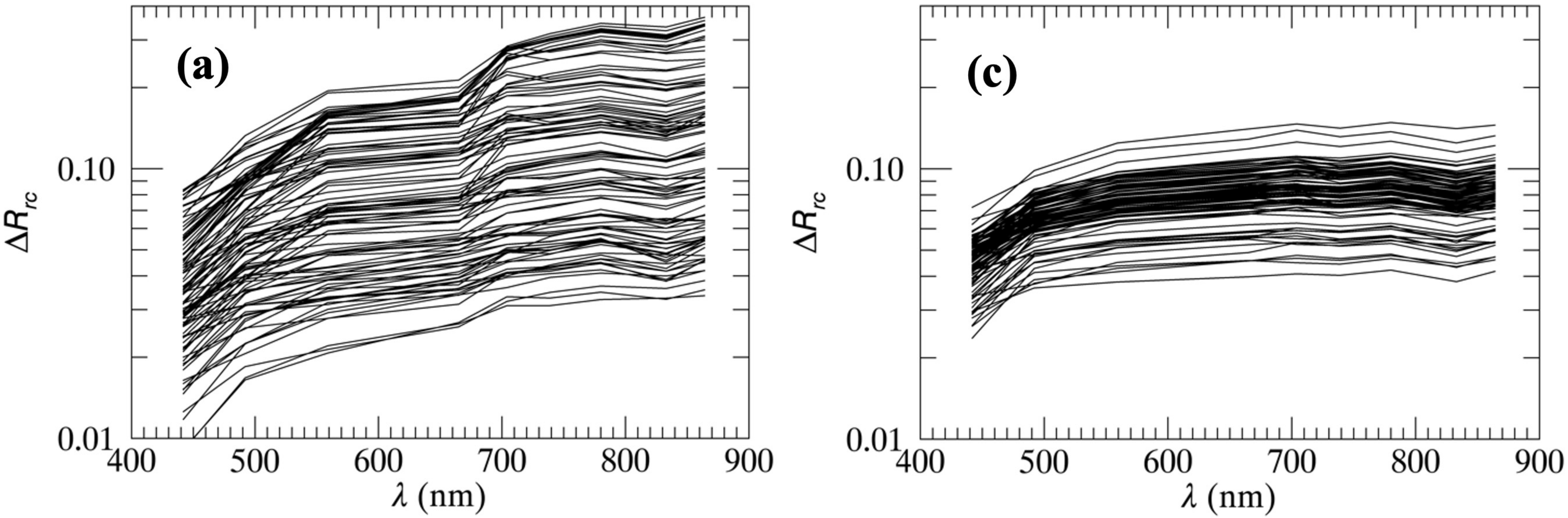
Qi et al. (2020); Hu (2021)

3. What can be done?

Second: spectral similarity

Spectral Angle Mapper (SAM) index (Kruse et al., 1993)

$$\text{SAM (degrees)} = \cos^{-1}[(\sum x_i y_i) / (\sqrt{\sum x_i^2} \sqrt{\sum y_i^2})]$$



Hu et al. (under review)

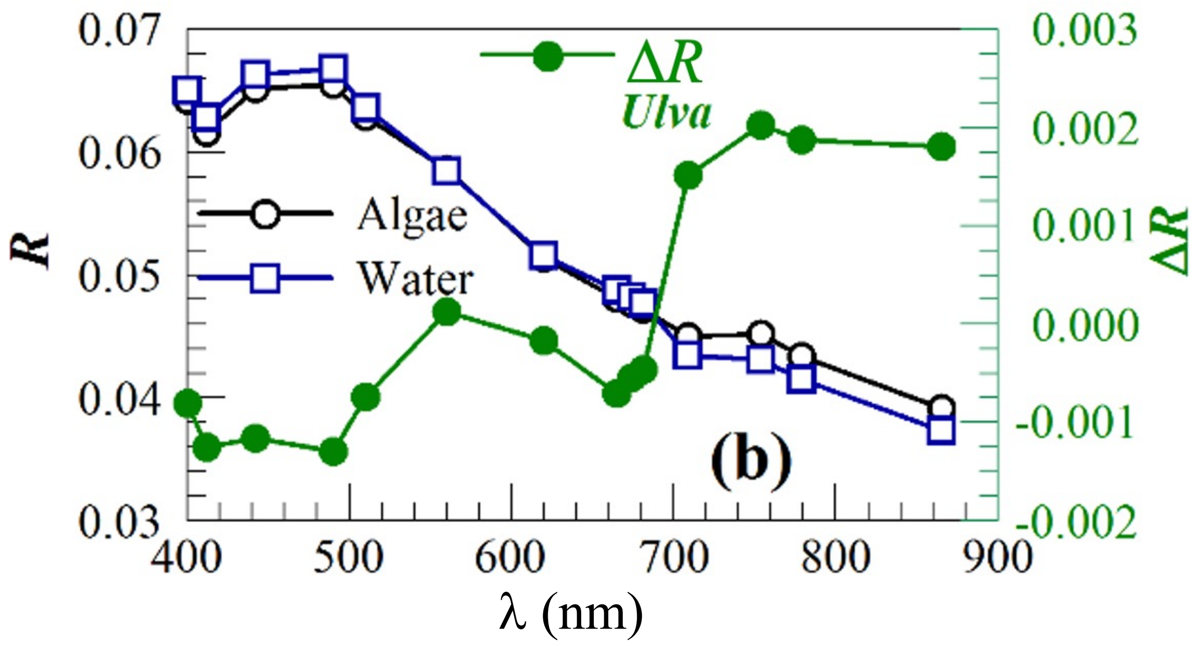
3. What can be done?

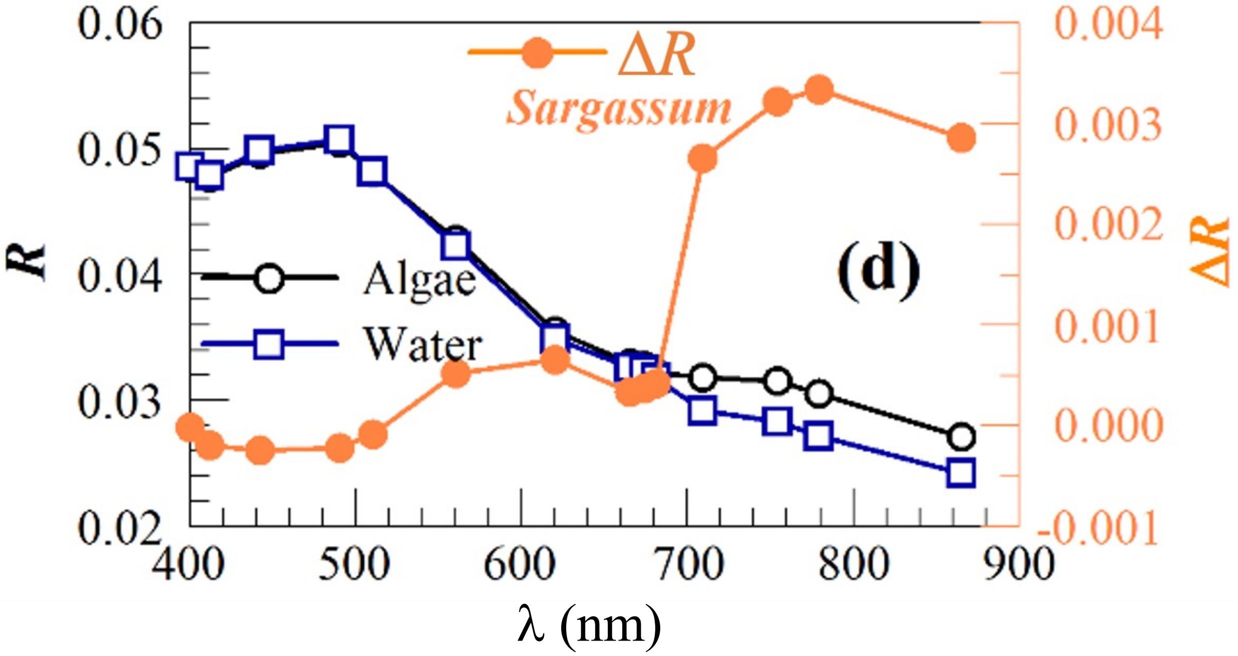
Second: spectral similarity

The key is to use the difference spectra (Gower et al., 2006)

$$R_{target} = \chi R_{\mathrm{FM}} + (1- \chi)R_{\mathrm{W}}$$

$$\Delta R = R_{target} - R_w = \chi(R_{\mathrm{FM}} - R_{\mathrm{W}})$$

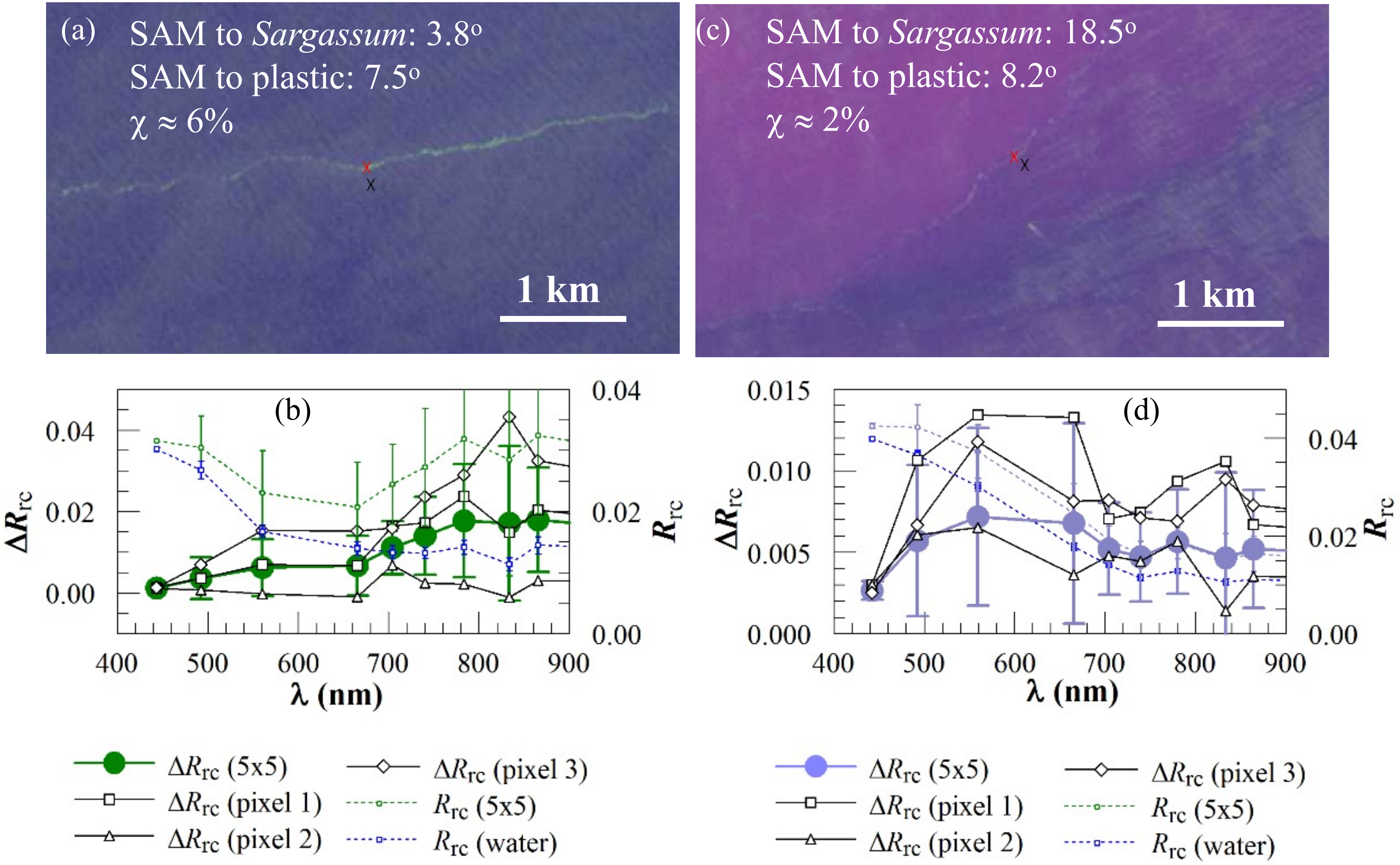




Qi and Hu (2021)

3. What can be done?

Second: spectral similarity; Third: pixel unmixing



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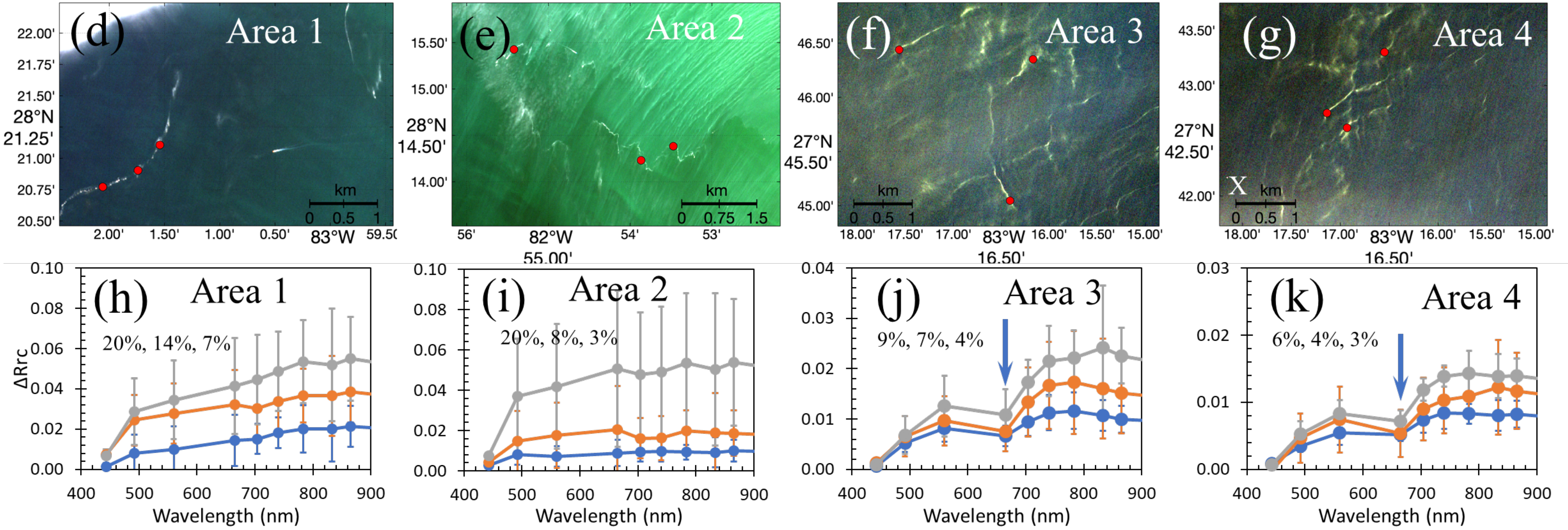
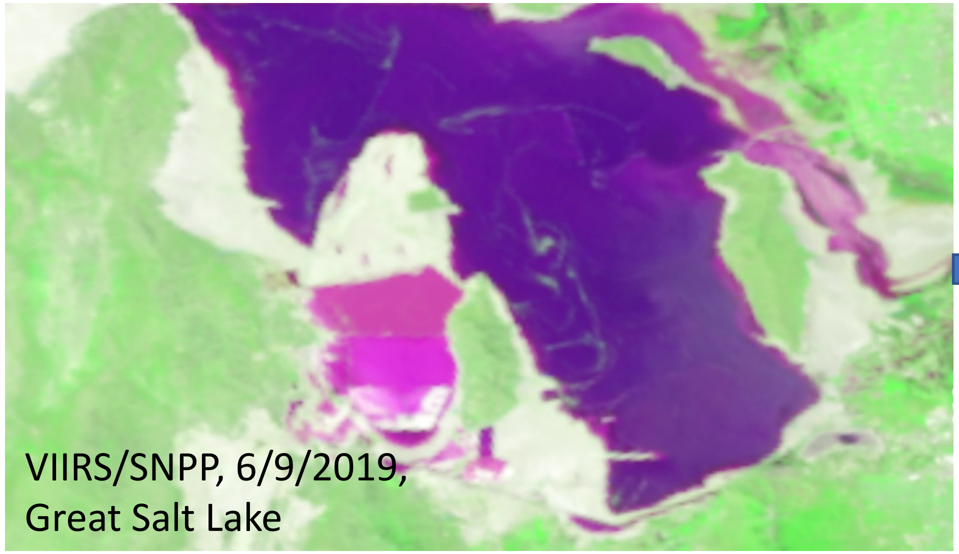
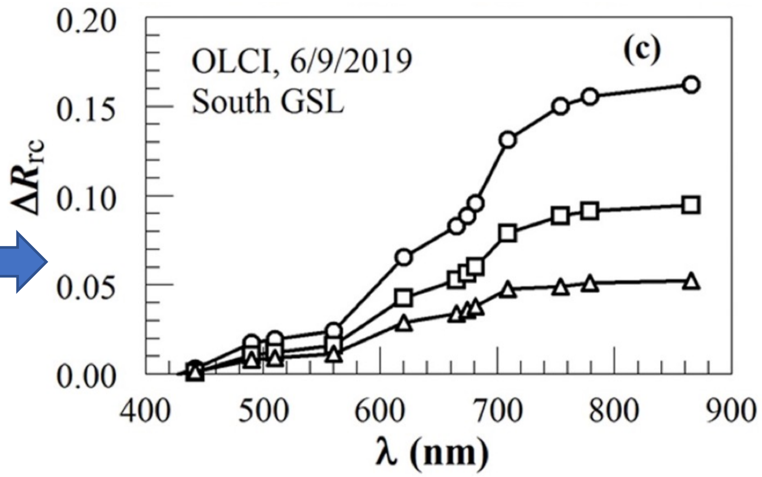


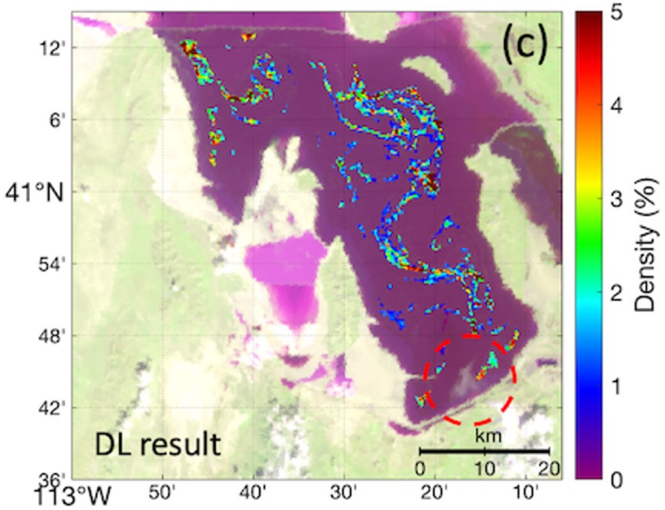
Hu (2021)

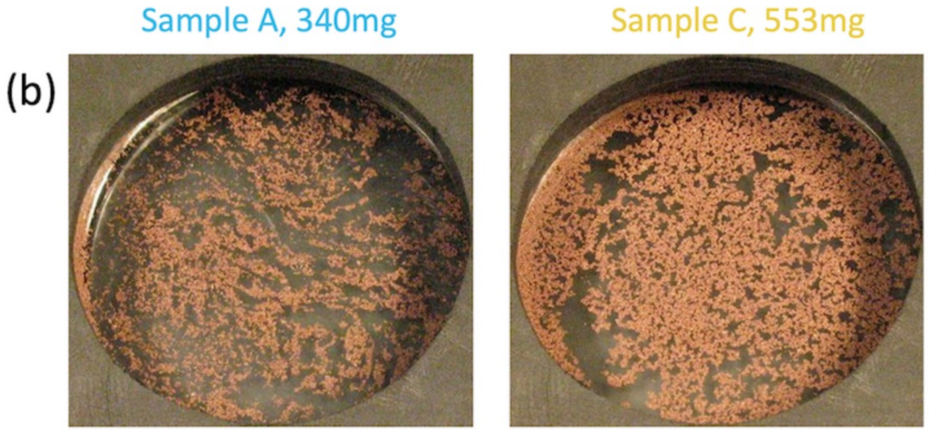
3. What can be done?

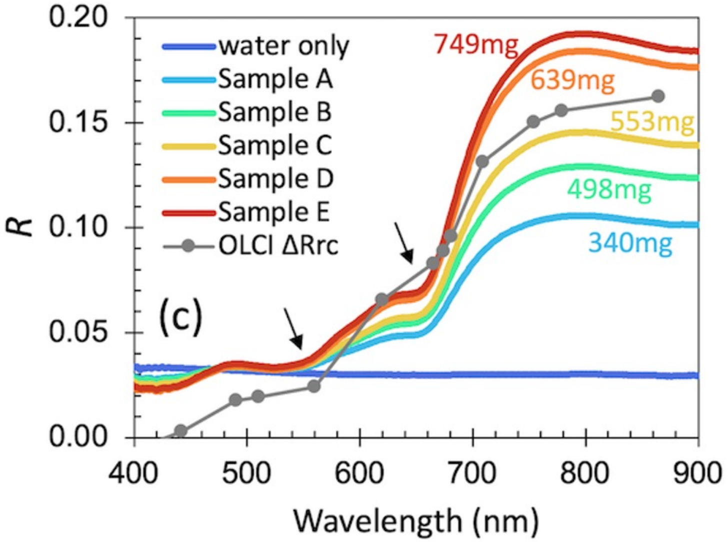
Second: spectral similarity; Third: pixel unmixing

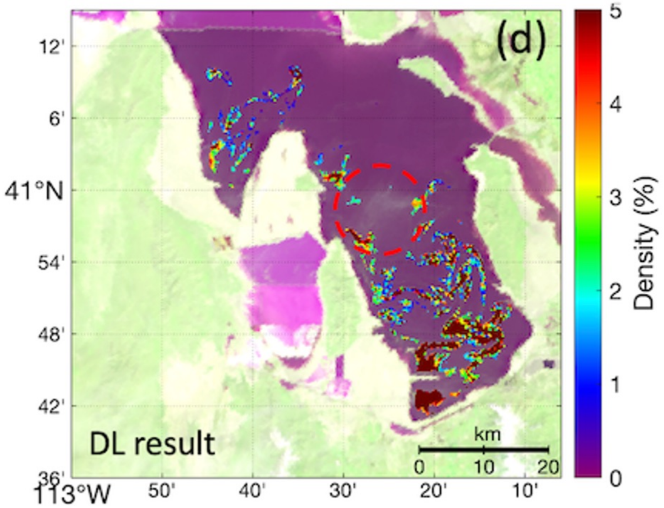








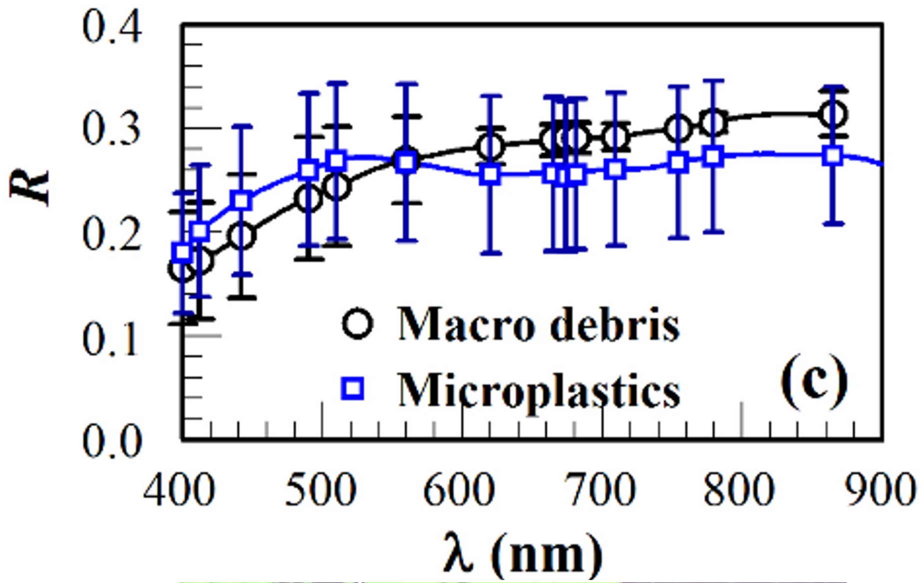


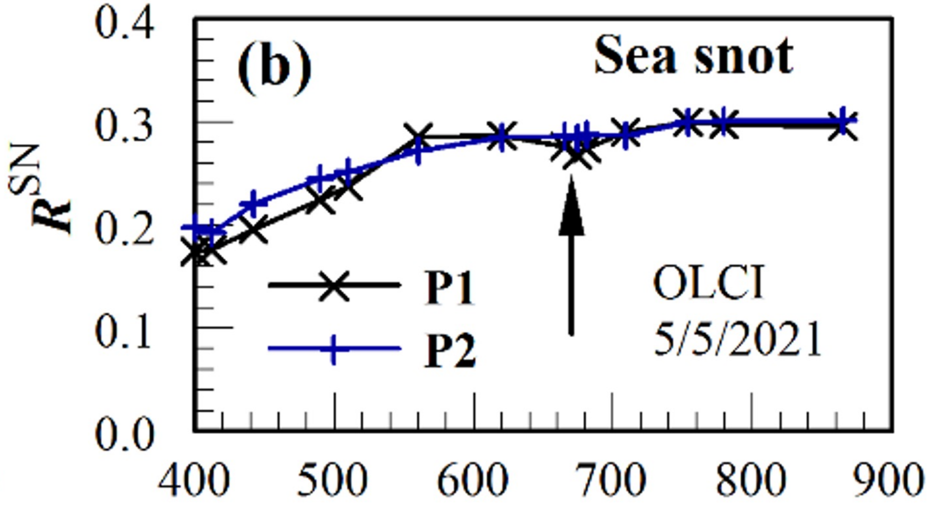


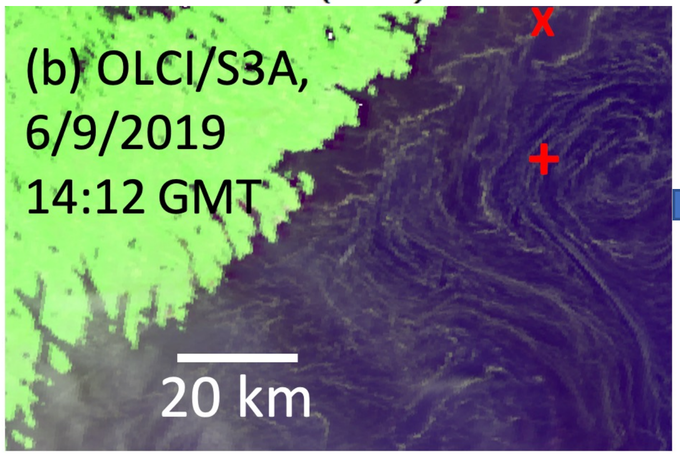
Qi et al. (2020 & 2021)

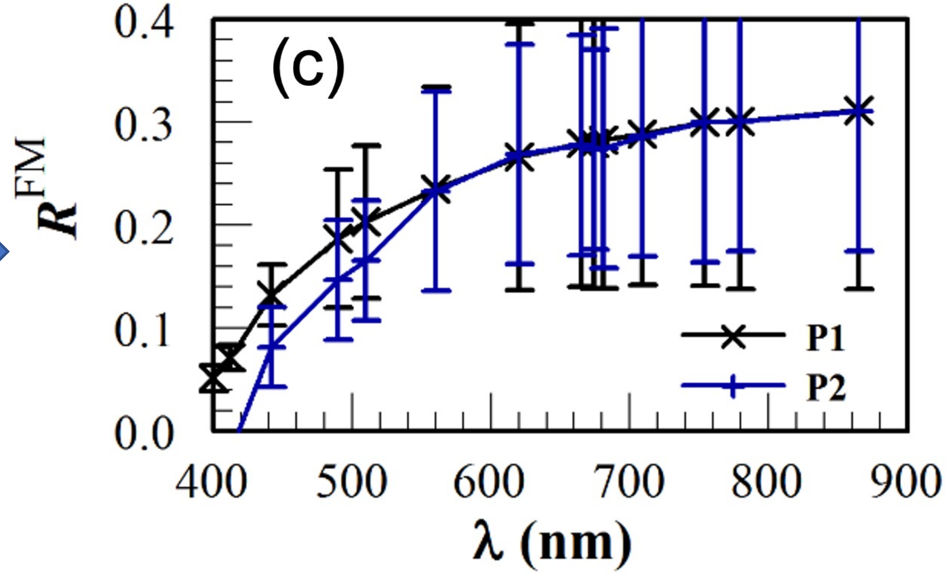
The difficulty with marine debris classification

Marine debirs is not the only floating matter with a flat spectral shape



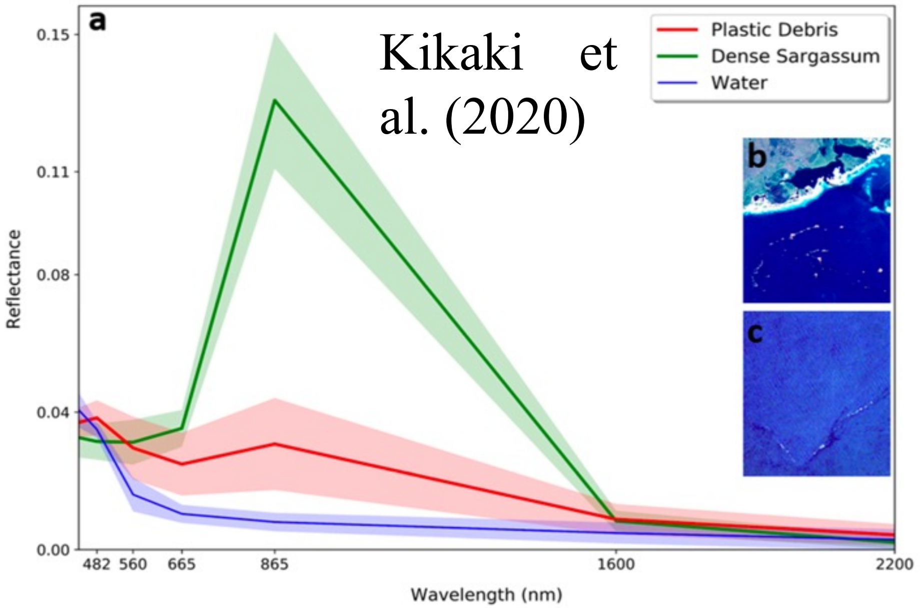


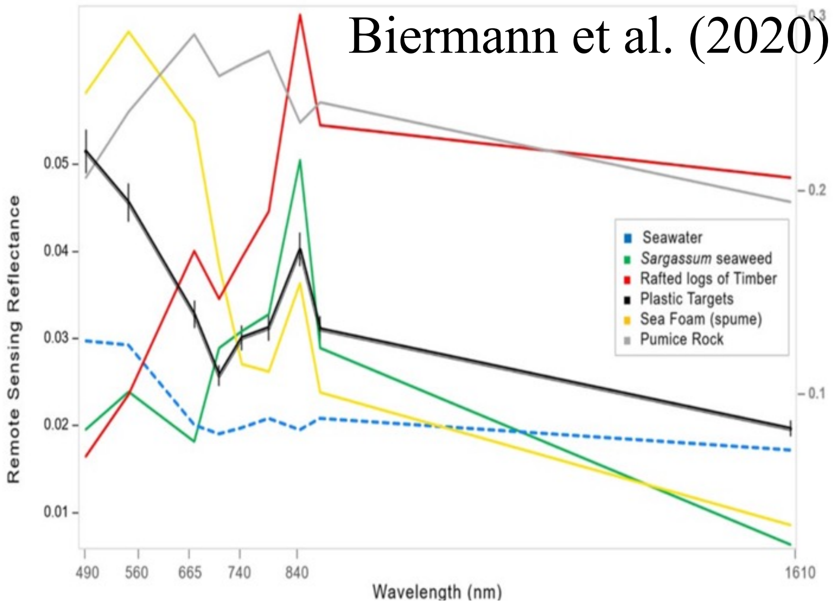


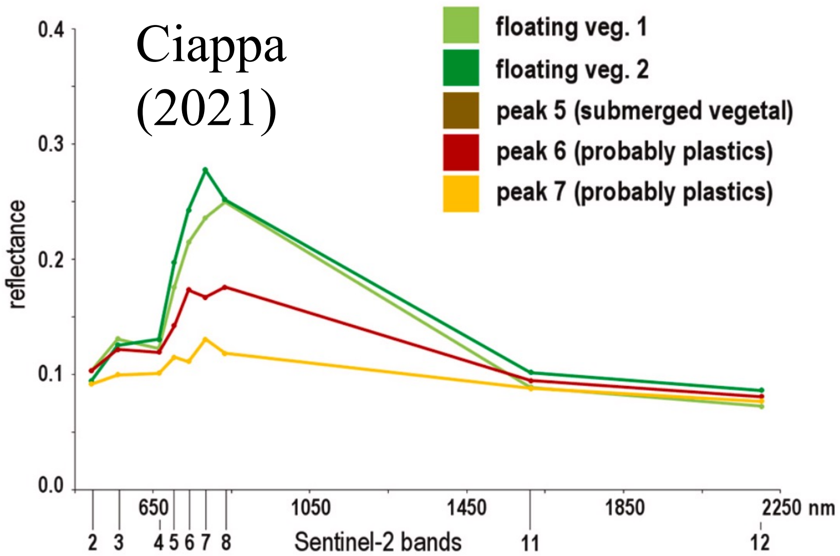


Common issues in the published literature

Spectral endmembers based on MSI data







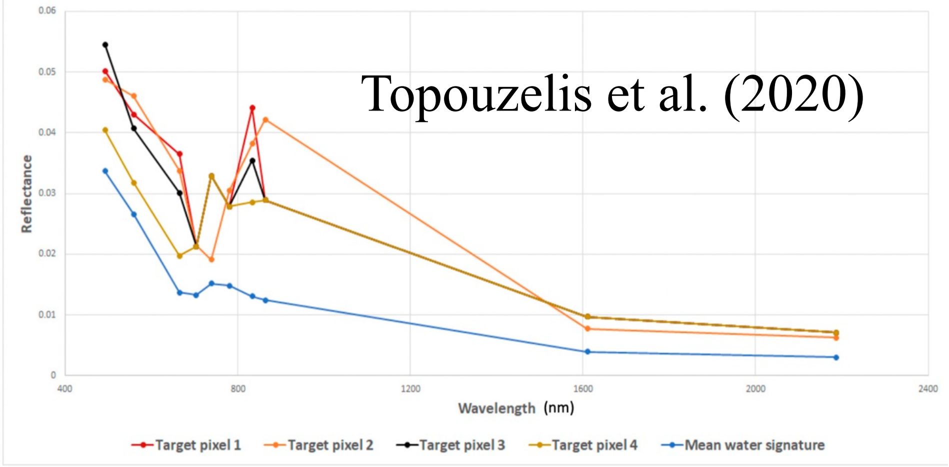
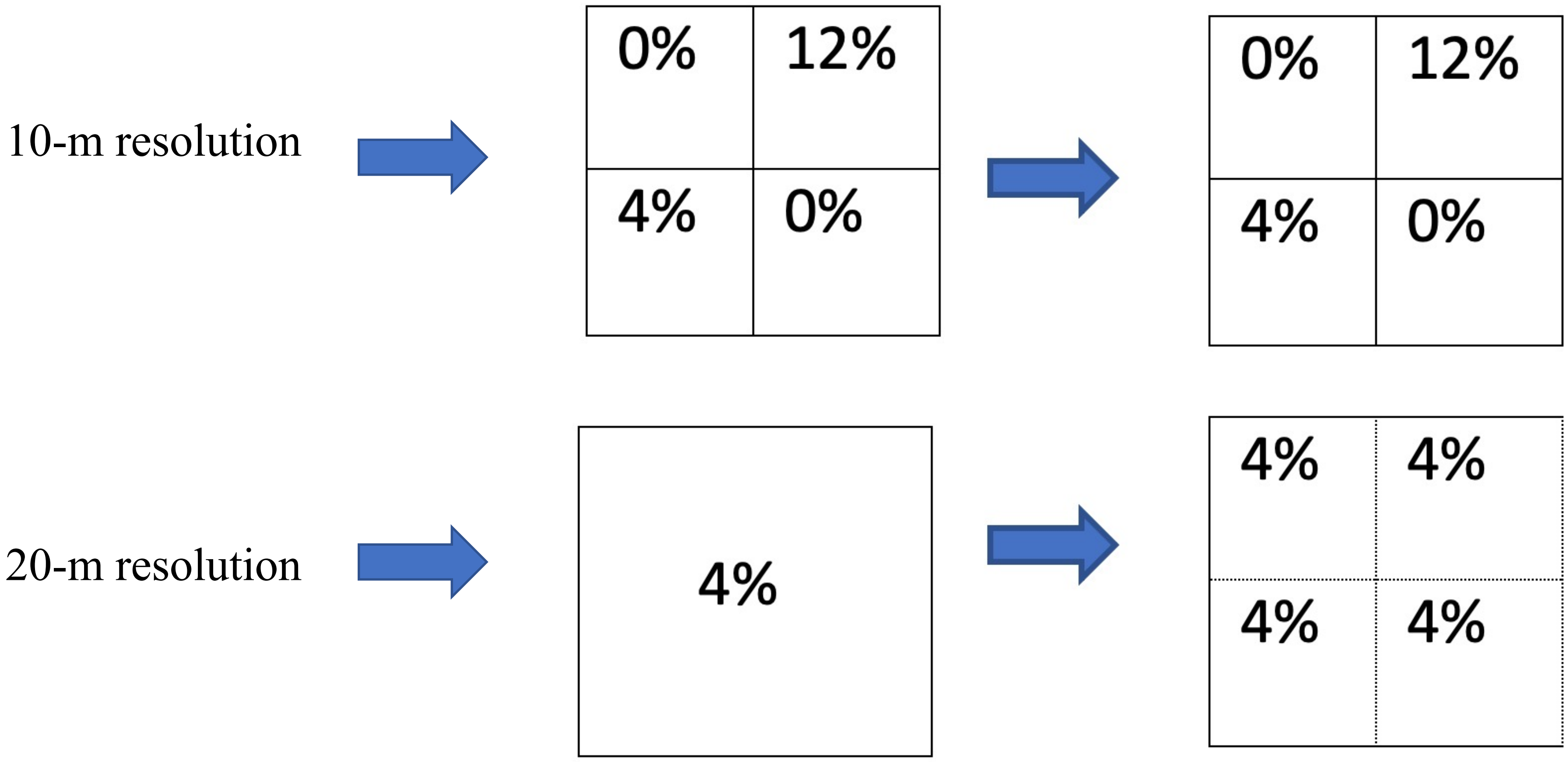


Figure 4. Spectral signature of the four detected target pixels on the 20190418 experimental date. The four Sentinel-2 pixels contain different percentage plastic coverage and are illustrated in the first row of Figure 5.

Common issues in the published literature

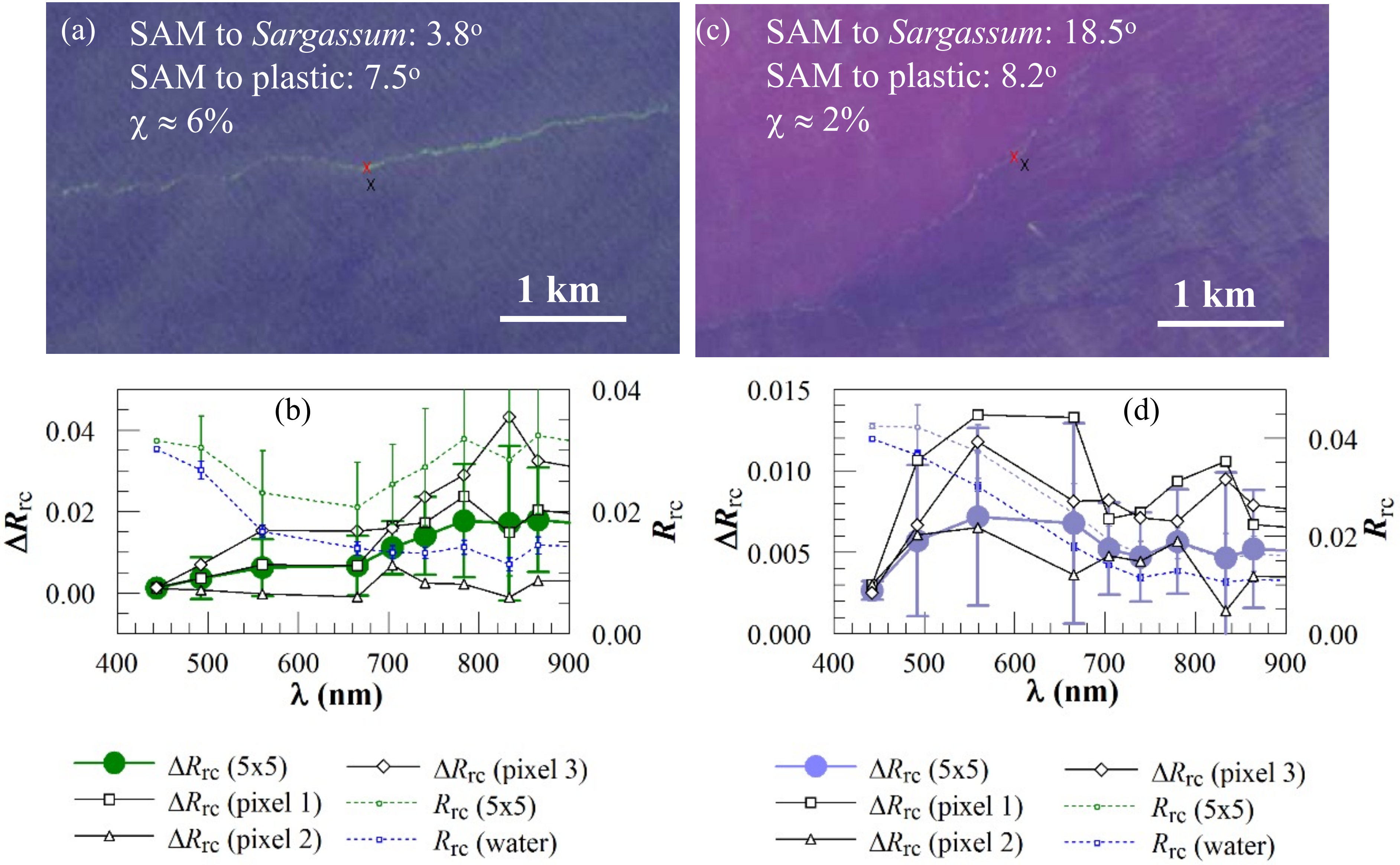
Spectral distortion due to mixed band resolution

For the same targets, Band X can be higher, lower, or equal to Band Y



Common issues in the published literature

Spectral distortion due to mixed band resolution



Common issues in the published literature

Spectral distortion due to sensor's parallax effect

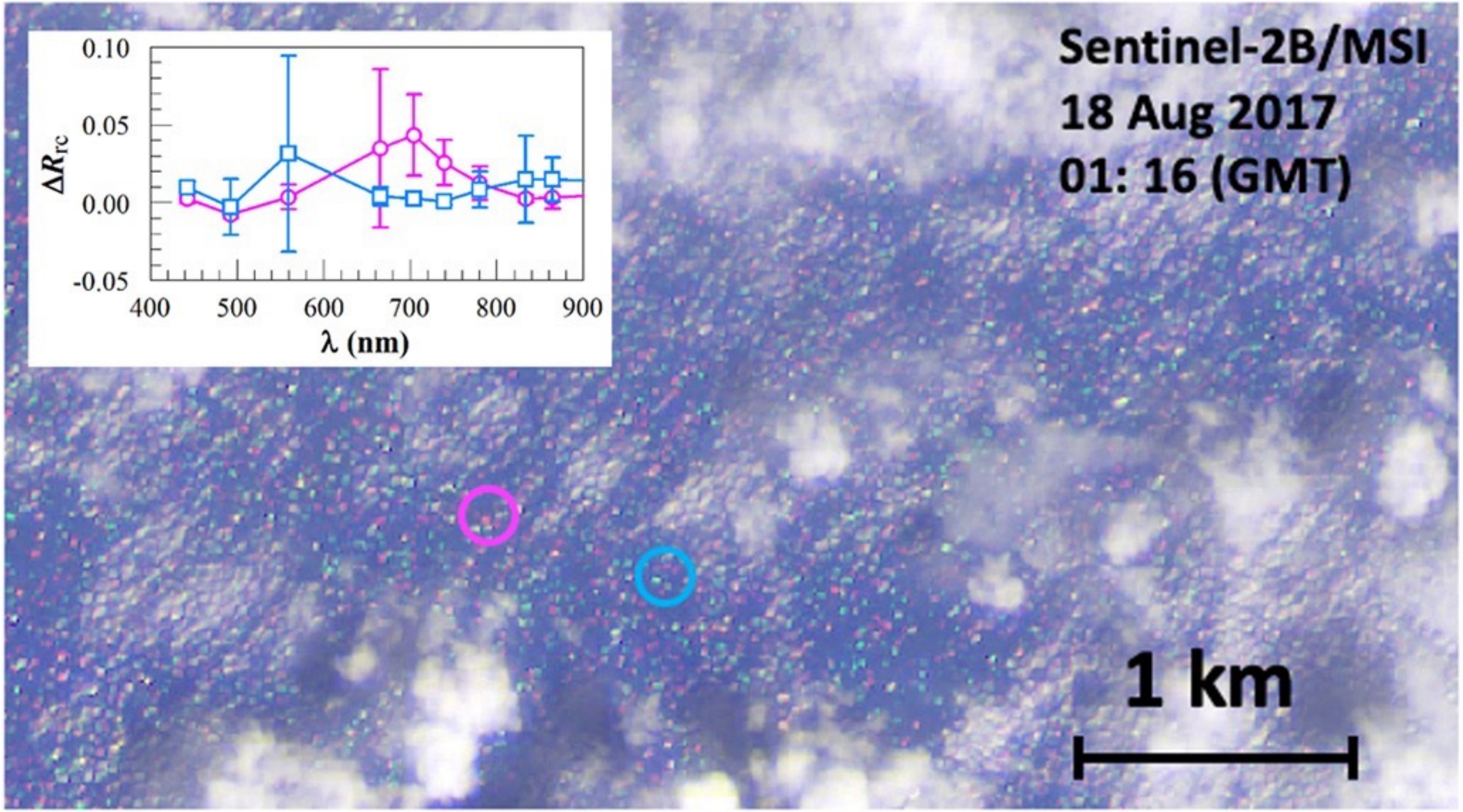


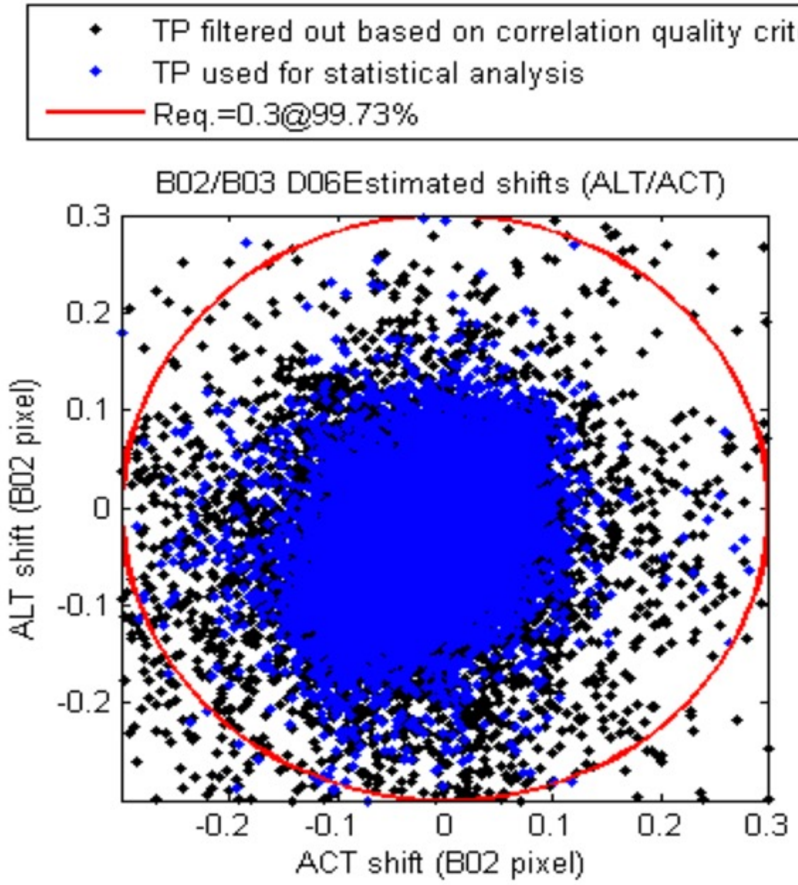
Image near Japan (Hu, 2021)

Common issues in the published literature

Spectral distortion due to mixed band resolution

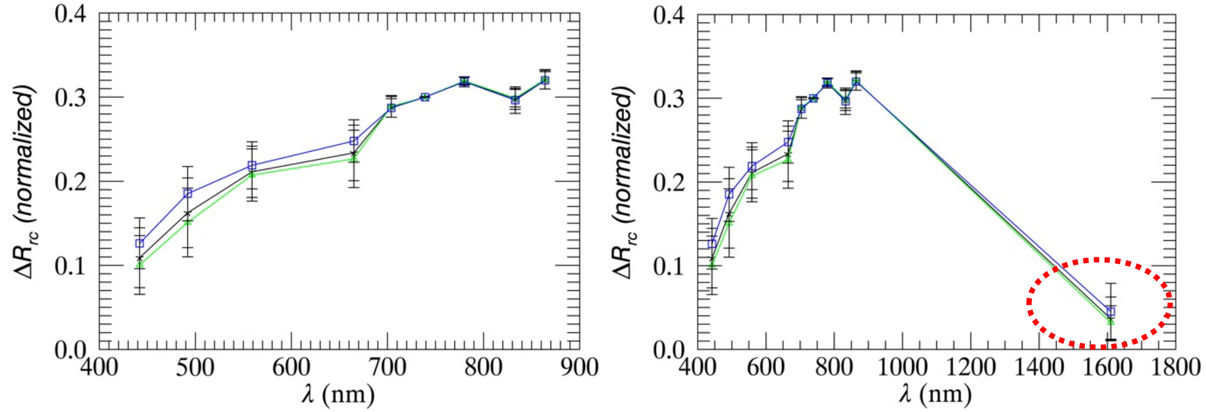
- ✓ Multi-spectral registration performances measured show that the mean circular error over all band couples and detectors is lower than 0.23 pixel of the coarser band.

Sentinel-2 OLCI band registration errors (Donlon et al., 2016)

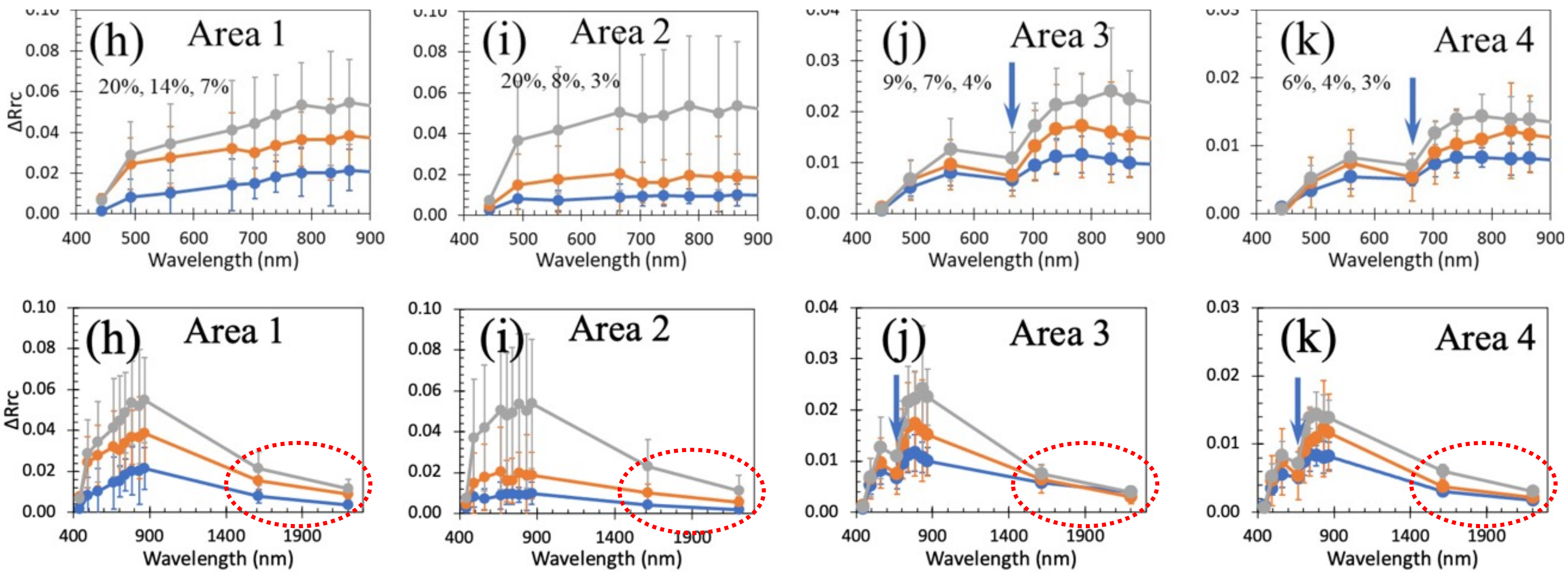


Any value in the SWIR bands?

MSI spectra of sea snot

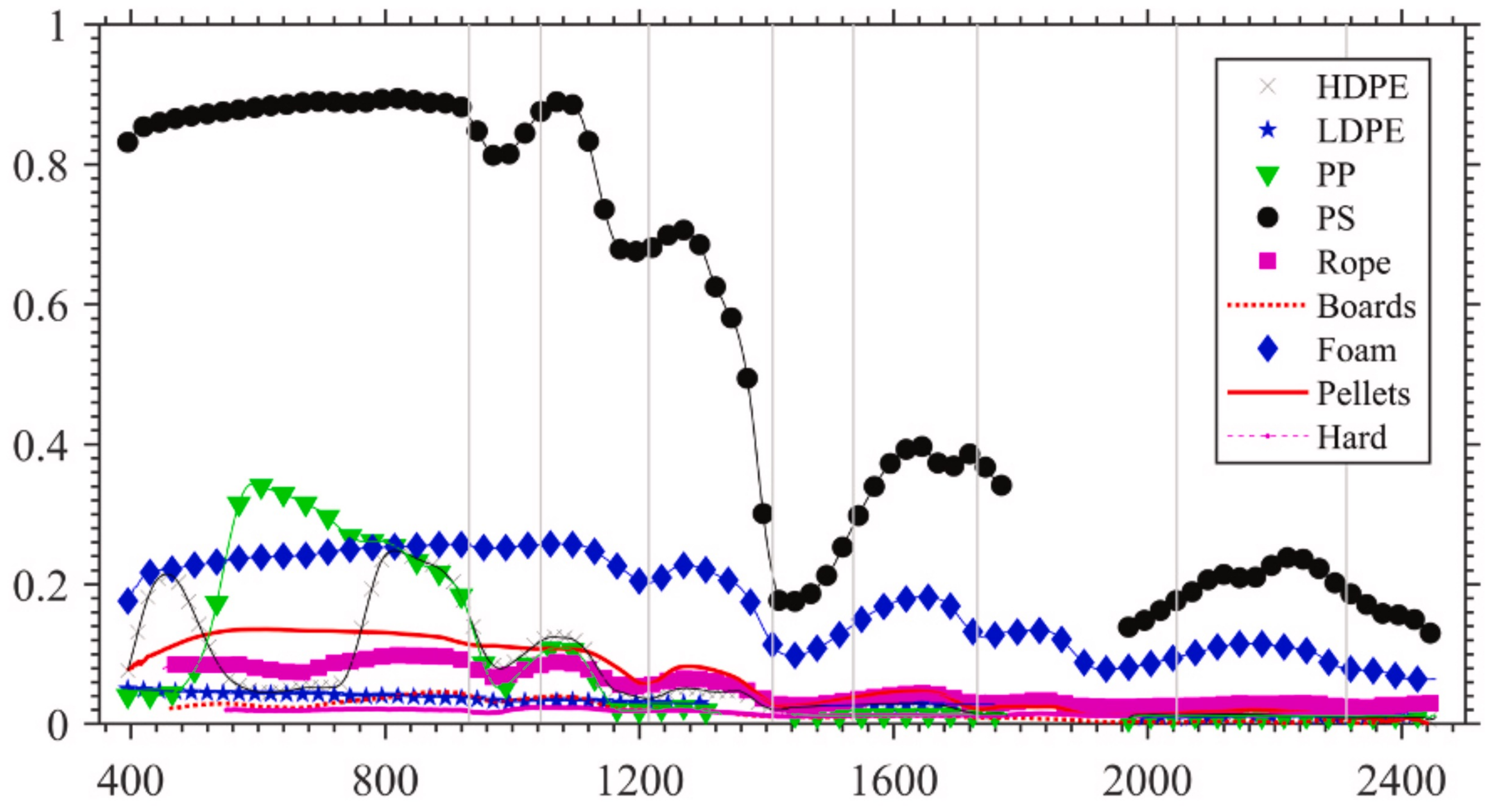


MSI spectra of Tricho and unknown floating matter



Any value in the SWIR bands?

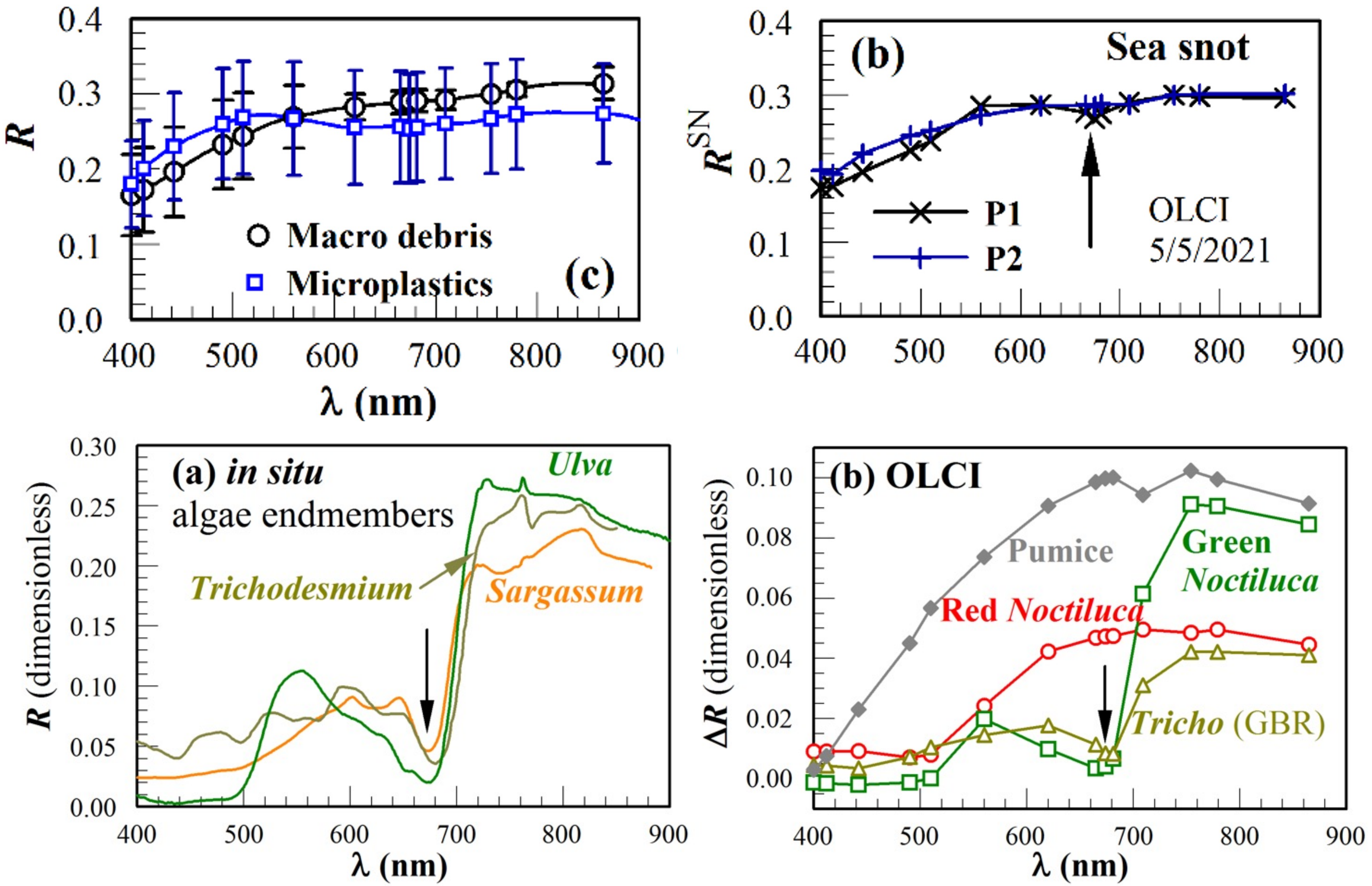
Plastics show C-H absorption features in several SWIR bands (Garaba et al., 2021)



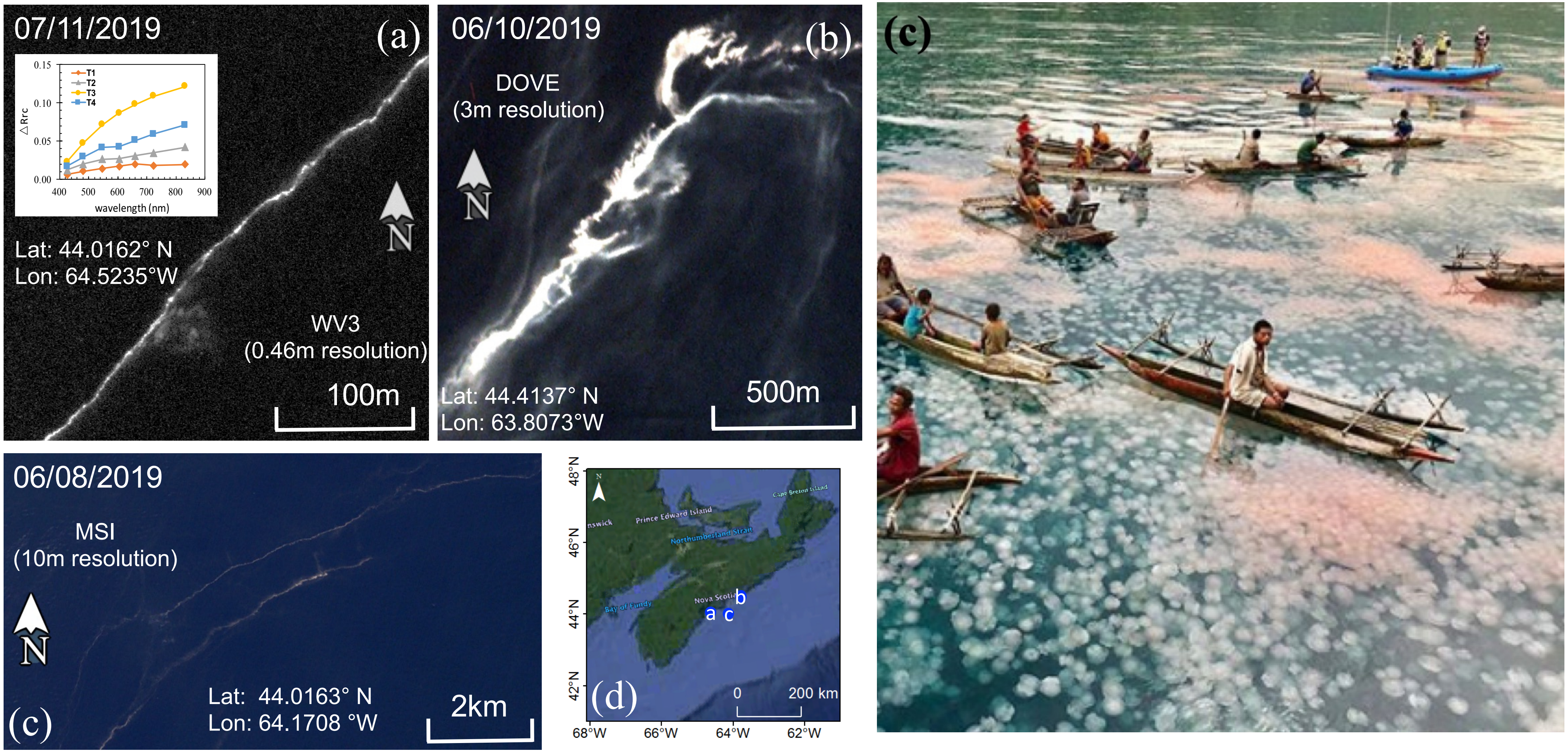
Without several additional bands around the absorption features, they can hardly be used as diagnostic features for plastics

Any value in hyperspectral data?

Yes for differentiating floating algae types, but no for differentiating marine debris types

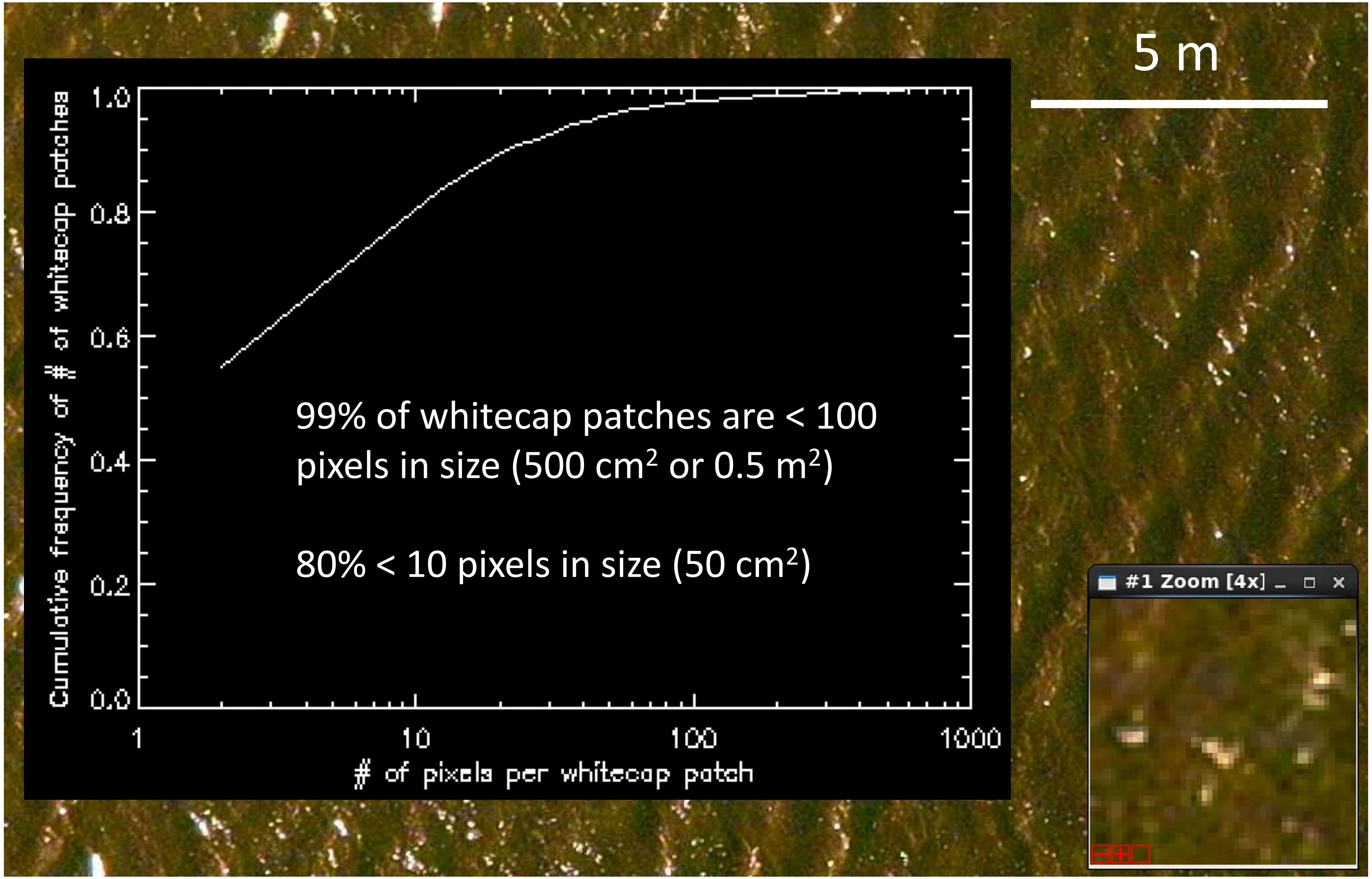


Any value in high resolution?



Any value in high resolution?

MicaSense multi-band image resolution: 2.2 cm/pixel



Summary – why is it so difficult and what can be done

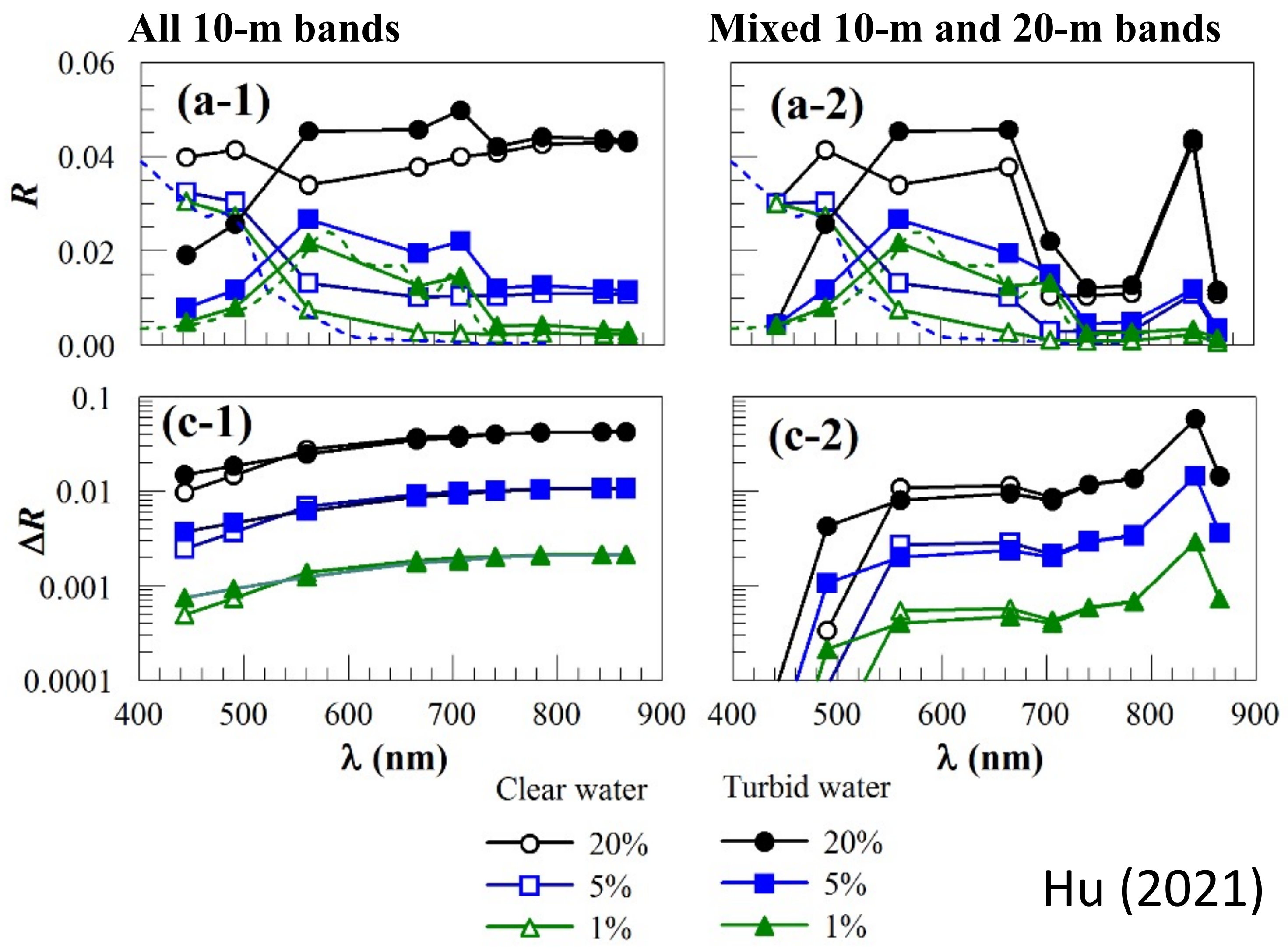
- Marine debris is typically small, thus appearing as a spatial anomaly in remote sensing imagery
- Lower detection limit of the anomaly depends on subpixel coverage (size matters!) and SNR
  - extremely difficult to detect microplastics
- Once an anomaly is detected, differentiating between floating vegetation and non-vegetation is easy using the 670-nm feature, but further discriminating the non-vegetation type (macro plastics, other debris, sea snot, etc) is very difficult because they are all spectrally flat
- Unmixing a mixed pixel is easy once a spatial anomaly is detected
- A critical requirement is to use the reflectance differencing technique to retain the spectral shape and to facilitate pixel unmixing
- A few discrete SWIR bands won't help, but more SWIR bands can be useful to "measure" the C-H features from polymers
- Hyperspectral data in the vis-NIR won't help differentiating various non-algae floating matters
- MSI provides an optimal trade between resolution and coverage, yet the mixed band resolution can distort spectral shape, thus requiring great caution. Pixel averaging and pixel differening are simple solutions – this also applies to other sensors
- All these points are conceptual, while implementing an automatic system requires a lot of work even for regional studies.

Take home messages

- Detecting “something” is relatively easy
- Discriminating that “something” is much more difficult
- We should not oversell the remote sensing capacity in detecting marine debris

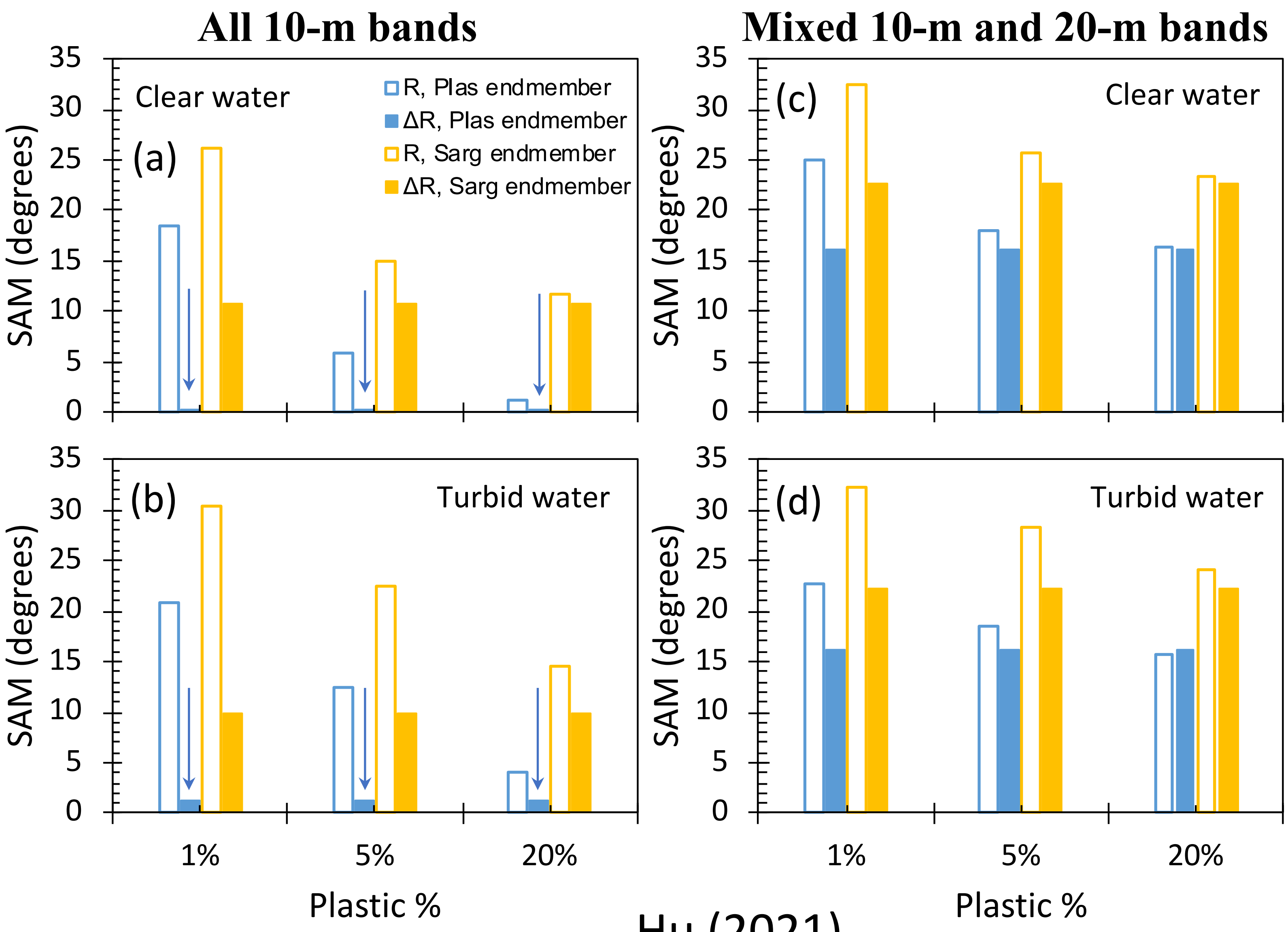
Supplemental slides

MSI mixed resolutions can distort spectral shapes



Hu (2021)

MSI mixed resolutions can distort spectral shapes



Hu (2021)