Autumnal Tints: Observing Fall Foliage from Space with PACE

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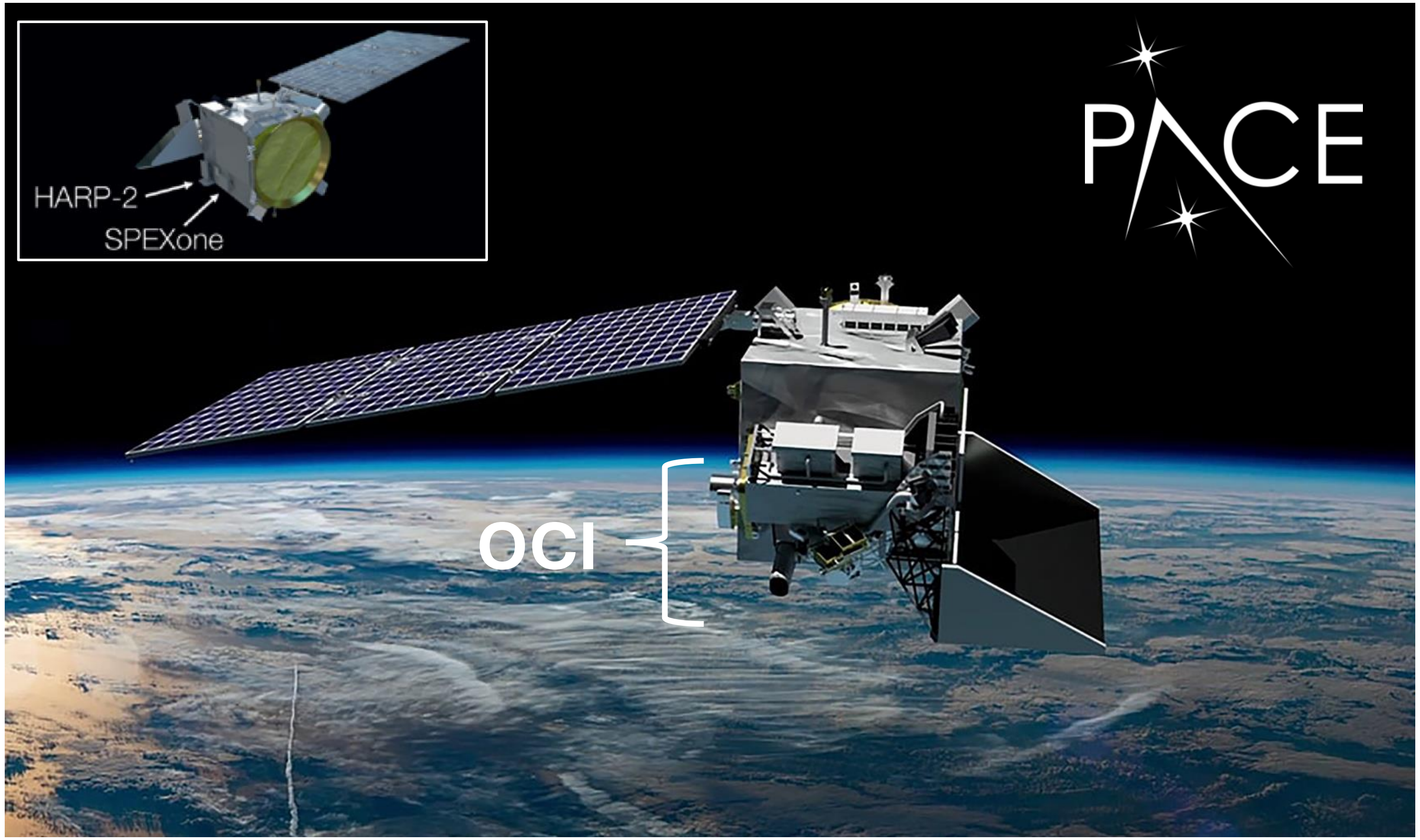
GLOBE Webinar, August 2026

PACE - Plankton, Aerosol, Cloud, ocean [& land!] Ecosystems

Although PACE's primary mission focus is ocean and atmosphere, it also provides a unique view of terrestrial ecosystems.



Launched on February 8, 2024, PACE carries three instruments:

- Ocean Color Instrument (OCI)– a hyperspectral imaging radiometer
- Two multi-angle polarimeters
  - HARP2 (Hyper-Angular Rainbow Polarimeter 2)
  - SPEXone (Spectro-polarimeter for Planetary Exploration one)

PACE's OCI has the unique capacity to produce global, repeated, spectral imagery that is leading to a new generation of remotely sensed products

Leaf Pigments

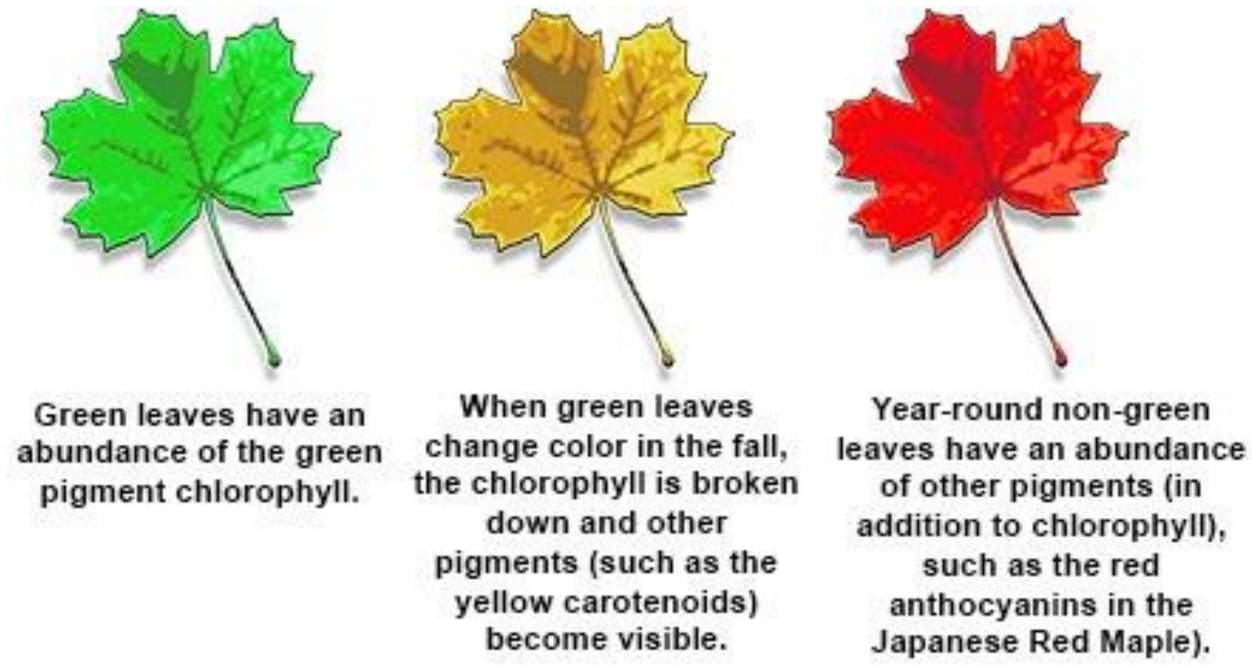
Autumn can be characterized by multiple phenological events, where one of the key events is the onset of leaf senescence

Chlorophyll – the fundamental pigment for photosynthesis. In the fall chlorophyll production slows then stops. Chl degrades so leaves can recover valuable elements- especially nitrogen (N) and magnesium- contained in their pigments.

Carotenoids are accessory pigments, absorbing light energy in the blue-green wavelengths to enhance photosynthesis; they also provide photoprotection when plants are stressed

Anthocyanins also provide photoprotection when plants are stressed and is an early indication of senescence. Most anthocyanins are produced in the autumn, in response to bright light and excess plant sugars within leaf cells.

Chlorophyll | Carotenoid | Anthocyanin



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PACE Vegetation Indices

PACE's hyperspectral measurements allow the calculation of indices related to foliar pigment content that are available as part of the PACE LANDVI products and are related to fall leaf color

CIRE - Chlorophyll Index Red Edge - canopy chlorophyll content, green pigments

$$CIRE = (\rho800/\rho705) - 1)$$

mARI - Modified Anthocyanin Reflectance Index - anthocyanin content, providing information on photoprotection and early indications of senescence, red pigments

$$mARI = [(1/\rho550) - (1/\rho705)] * \rho800$$

Car - Carotenoid Content Index - canopy carotenoid content, which gives insight on photosynthesis and photoprotection, yellow pigments

$$Car = [(1/\rho495) - (1/\rho705)] * \rho800$$

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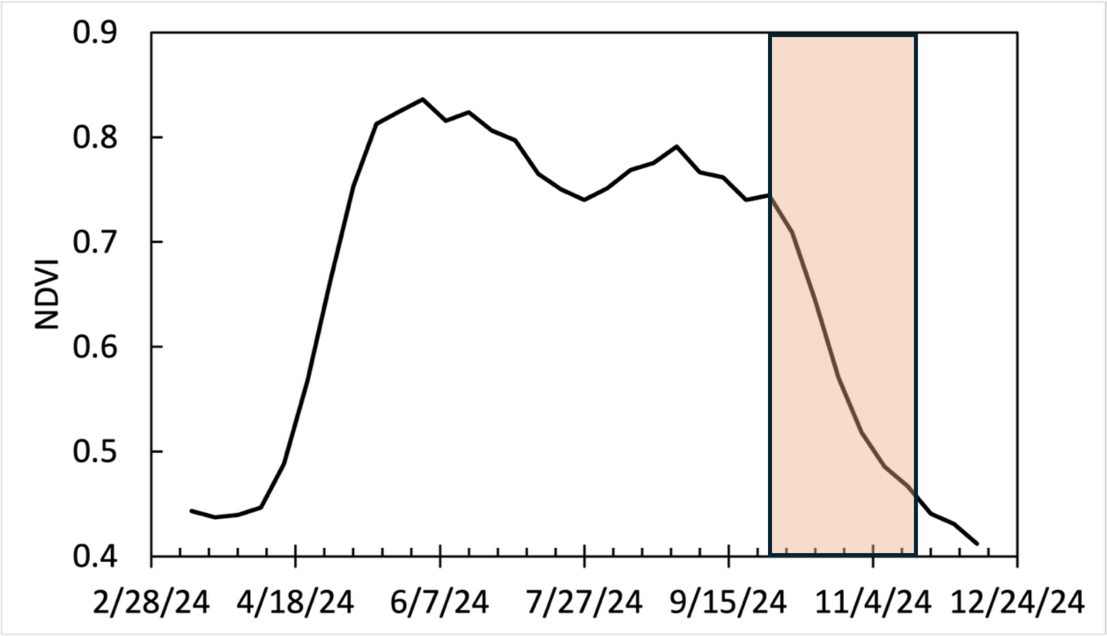
Remote Sensing of Phenology

- Many remote sensing studies of ecosystem phenology use broadband greenness indices such as NDVI or EVI
- These indices respond to green leaf area and are affected by both leaf area and leaf chlorophyll content
  - Thus, changes in leaf color must be inferred from the seasonal greenness index curve



Typical Deciduous forest NDVI seasonal curve, leaf color change occurs some time in the orange shaded area during a period of steady decline in NDVI

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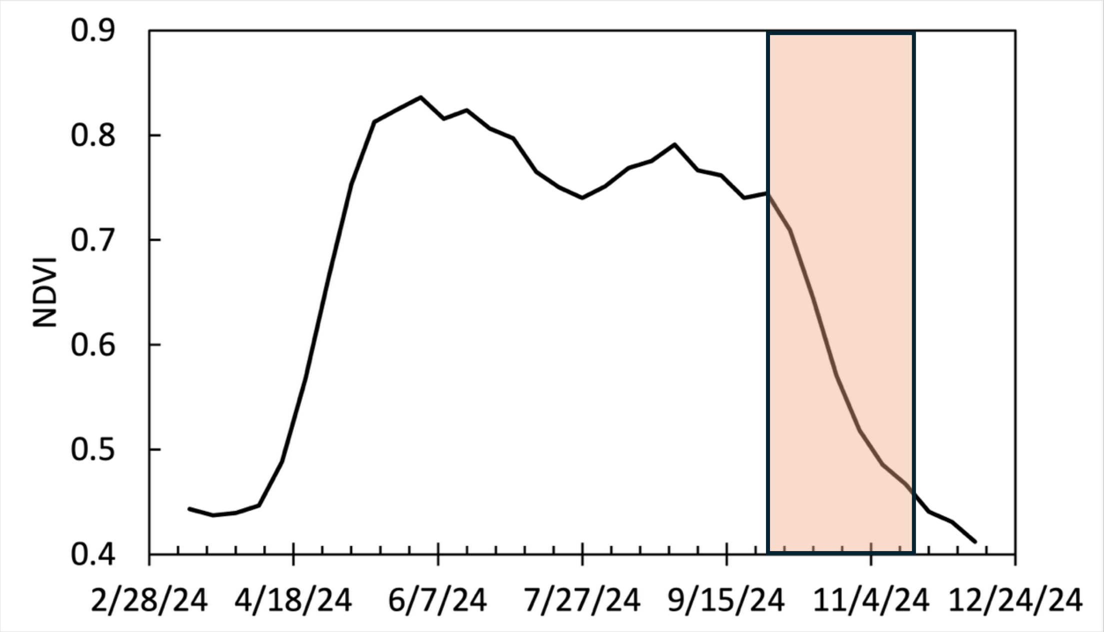
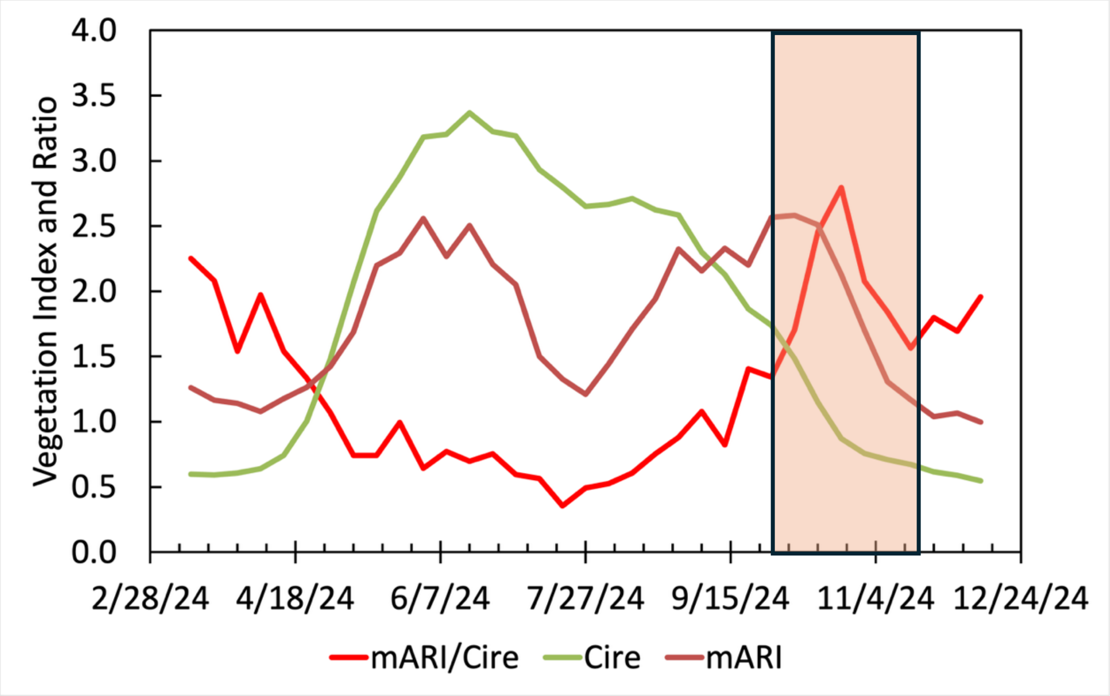
Remote Sensing of Phenology

The regular repeat observations of PACE pigment indices reveal physiological processes and their timing unseen by the greenness indices

Typical Deciduous forest seasonal NDVI curve, leaf color change occurs some time in the orange shaded area during a period of steady decline in NDVI



Deciduous forest seasonal PACE Pigment Index curves, illustrating how the pigment ratio (mARI/Cire, red line) shows a clear progression of fall colors and timing of peak color



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Pigment Ratios

The value of a pigment vegetation index (e.g., Cire or mARI) is related to the amount of the pigment in the leaves and the total leaf area (LAI*leaf pigment content)

By taking the ratio of two of these indices (e.g., mARI/Cire) we minimize the effect of leaf area and highlight the the change in relative leaf pigment pool sizes affecting leaf colors

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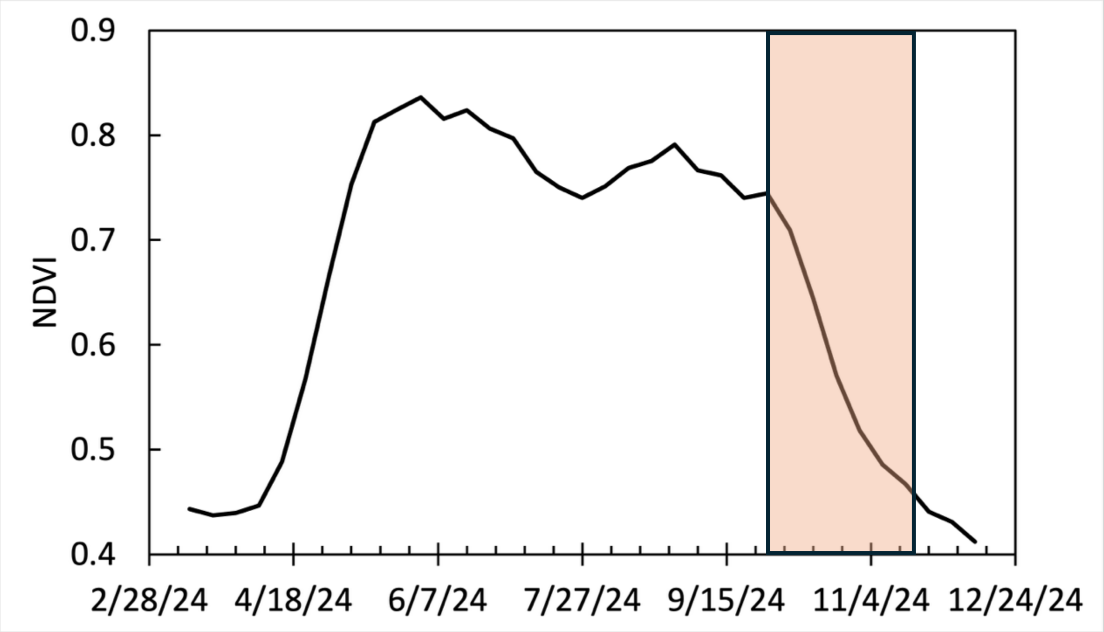

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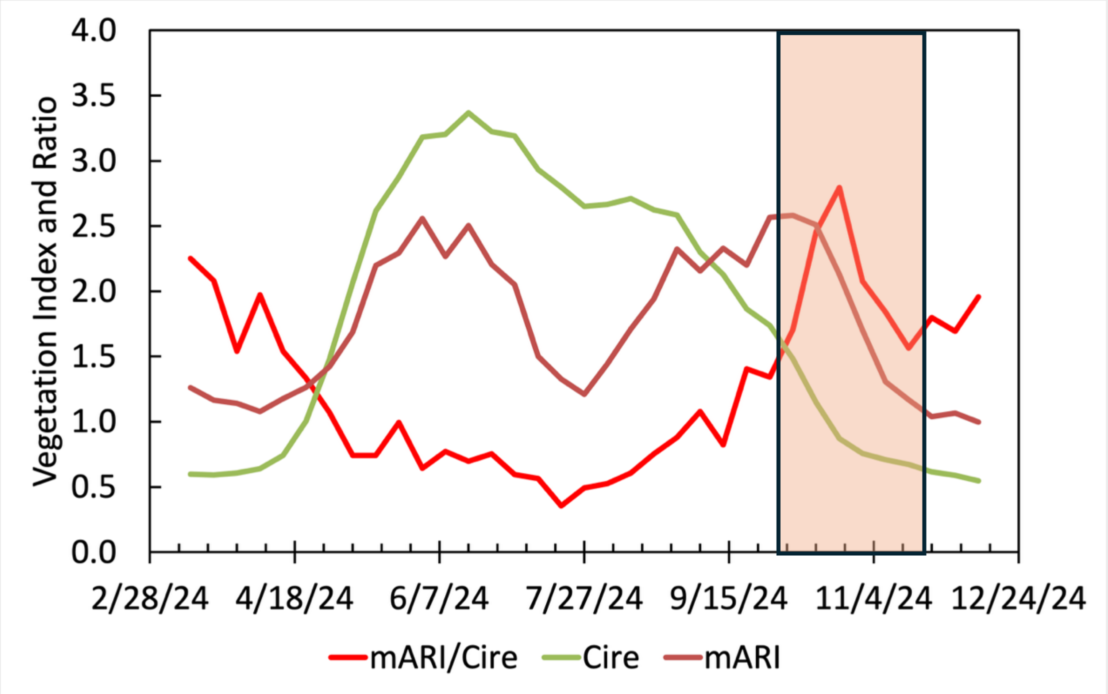

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Autumnal Tints from PACE – Pigment Ratio and Redness

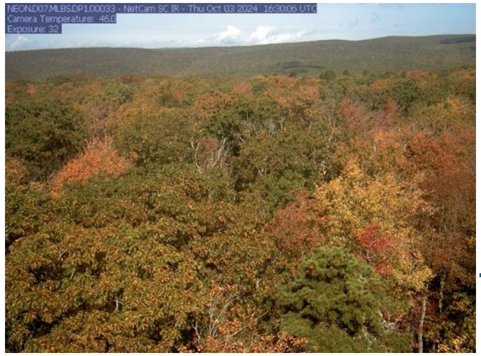
The PACE pigment index ratio (e.g., mARI/Cire) describes variations in relative pigment contents in leaves, but does it describe the color changes we observe in the leaves?

Compare with measurements from phenocams that provide webcam photos of forests

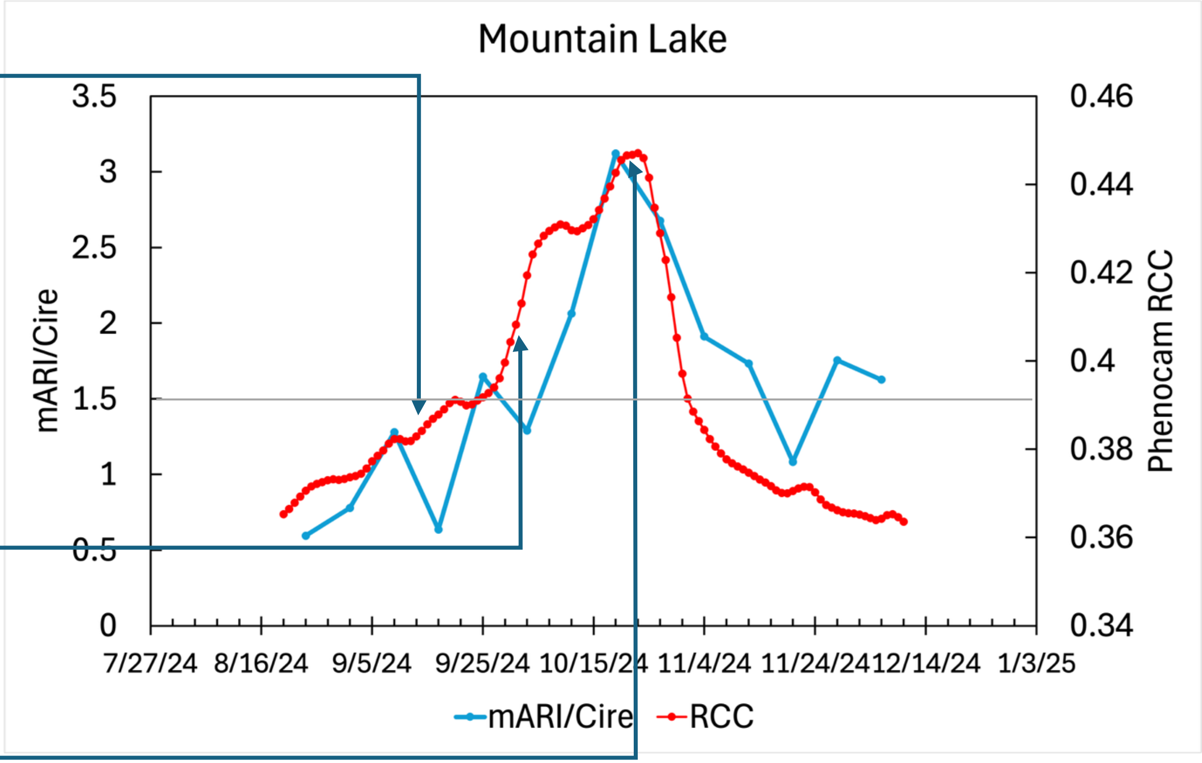
The red chromatic coordinate (RCC=R/(R+G+B)) a measure of scene redness is used to quantify leaf color change

9/16/24
Green

10/3/24
Early
color



10/23/24
Max color



Matching PACE pigment ratio (blue points) with redness from Phenocam photos (red points).
Estimate pigment ratios >1.5 for forests with fall colors

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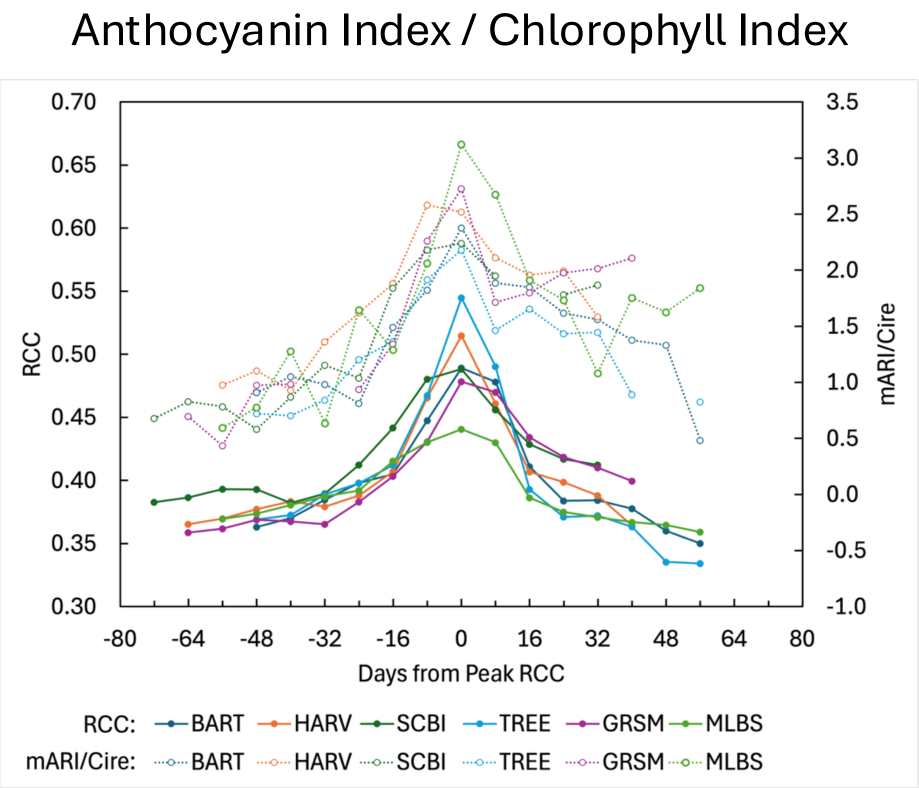
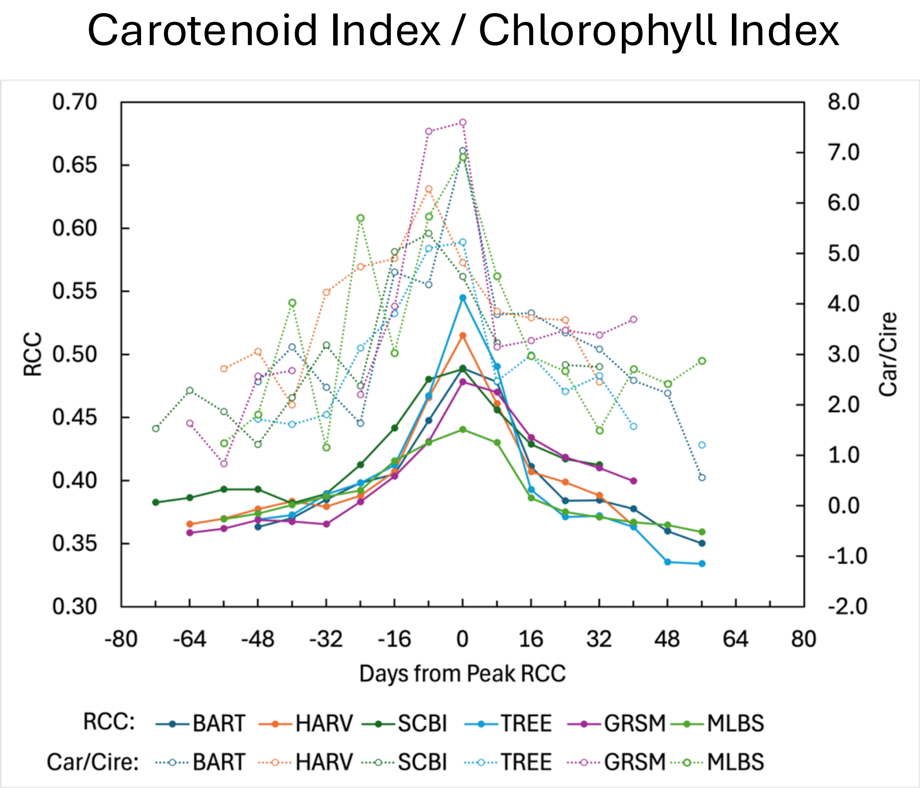
Autumnal Tints from PACE – Comparison with Phenocam Data





Autumn 2024 8-day average 4 km PACE index ratios (mARI/Cire and Car/Cire) (dotted lines) for six deciduous forest NEON flux tower sites

Daily smoothed Phenocam Red Chromatic Coordinate (RCC = R/(R+G+B)) averaged to match PACE 8-day averages used as ground data (solid lines) (https://www.neonscience.org/data-collection/phenocams)

To compare the seasonal change in color across the sites, the times are shifted so that the date of RCC peak is 0 on the x-axis.

RCC peak dates vary across the six sites from October 7 to October 31 for the 8-day average start dates.

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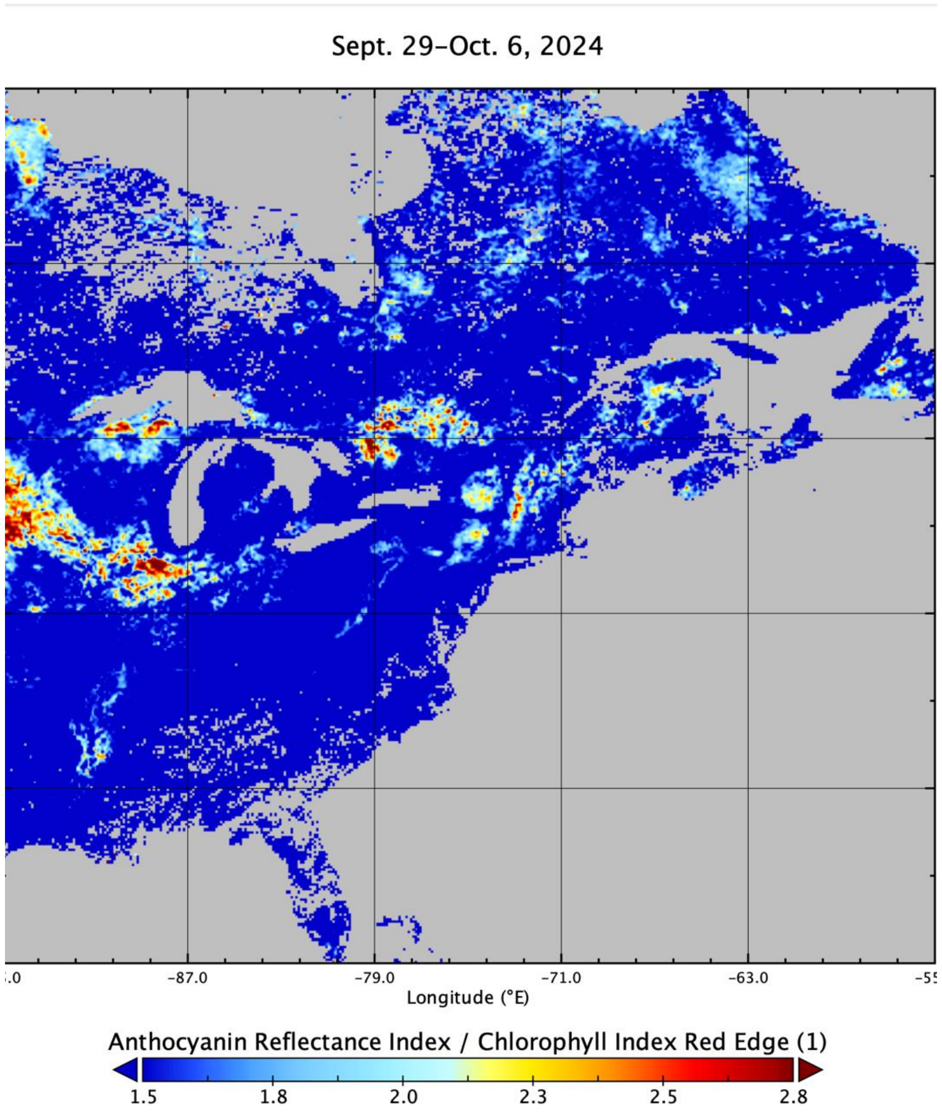
Autumnal Tints from PACE

PACE Pigment Ratio (mARI/Cire)
8-day averages, ~6x11 km cells
PACE data from NASA Earthdata
(https://search.earthdata.nasa.gov/)

In this early fall image, fall colors are beginning in higher elevation deciduous forests in the White Mountains in New Hampshire, the Green Mountains in Vermont, the southern Laurentian Mountains in southern Quebec, the Adirondack Mountains, the Catskills, and the North Woods in northern Wisconsin and Mich upper peninsula.



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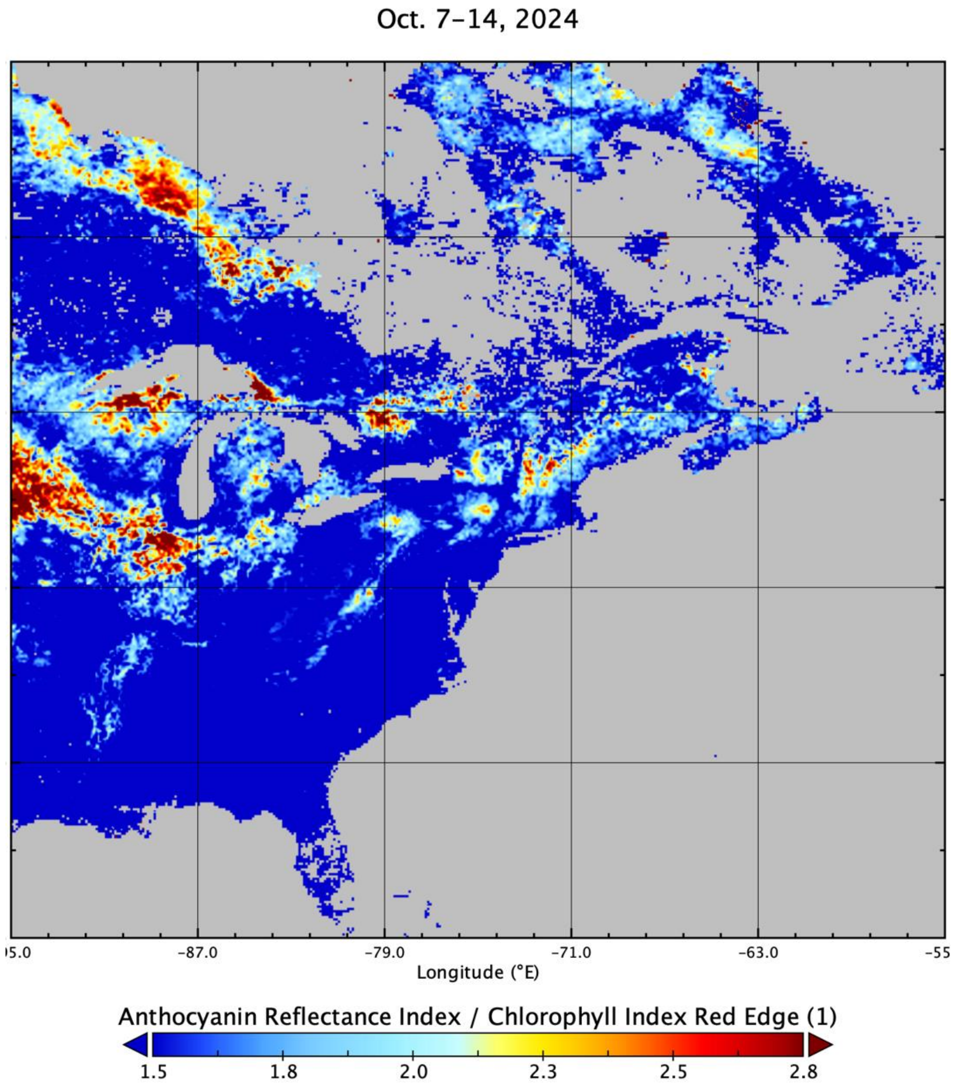
Autumnal Tints from PACE

In addition to the higher elevation deciduous forests there is now a signal in the Hudson Bay lowlands, a peaty marshy muskeg area south of Hudson Bay. These lowlands may be a major natural source of atmospheric methane.
Fall colors begin to appear in the High Allegheny Plateau in central Pennsylvania and in the Central Appalachians in West Virginia



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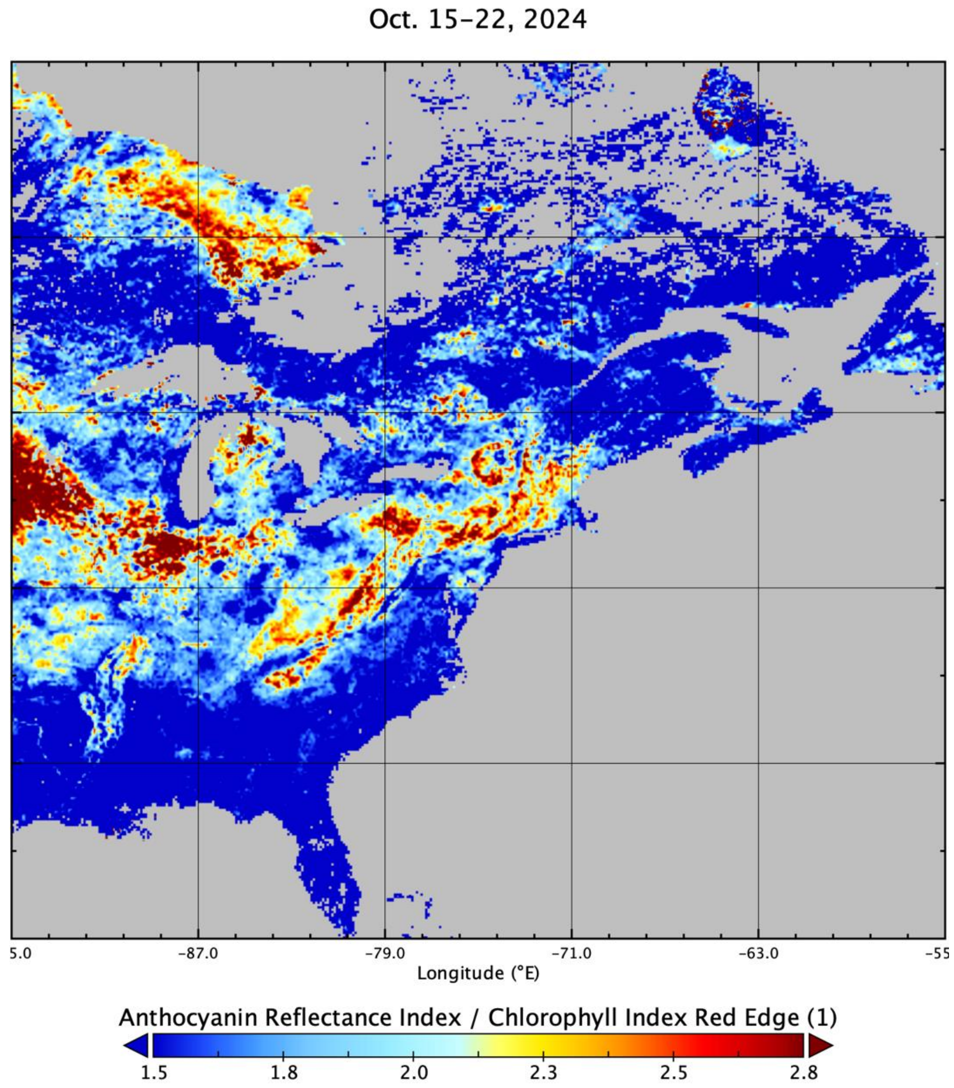
Autumnal Tints from PACE

As we move further into fall, notice how the colors have moved to lower elevations in the arc of the Adirondack Foothills

In addition, fall colors are now running down the length of the Appalachian Mountains



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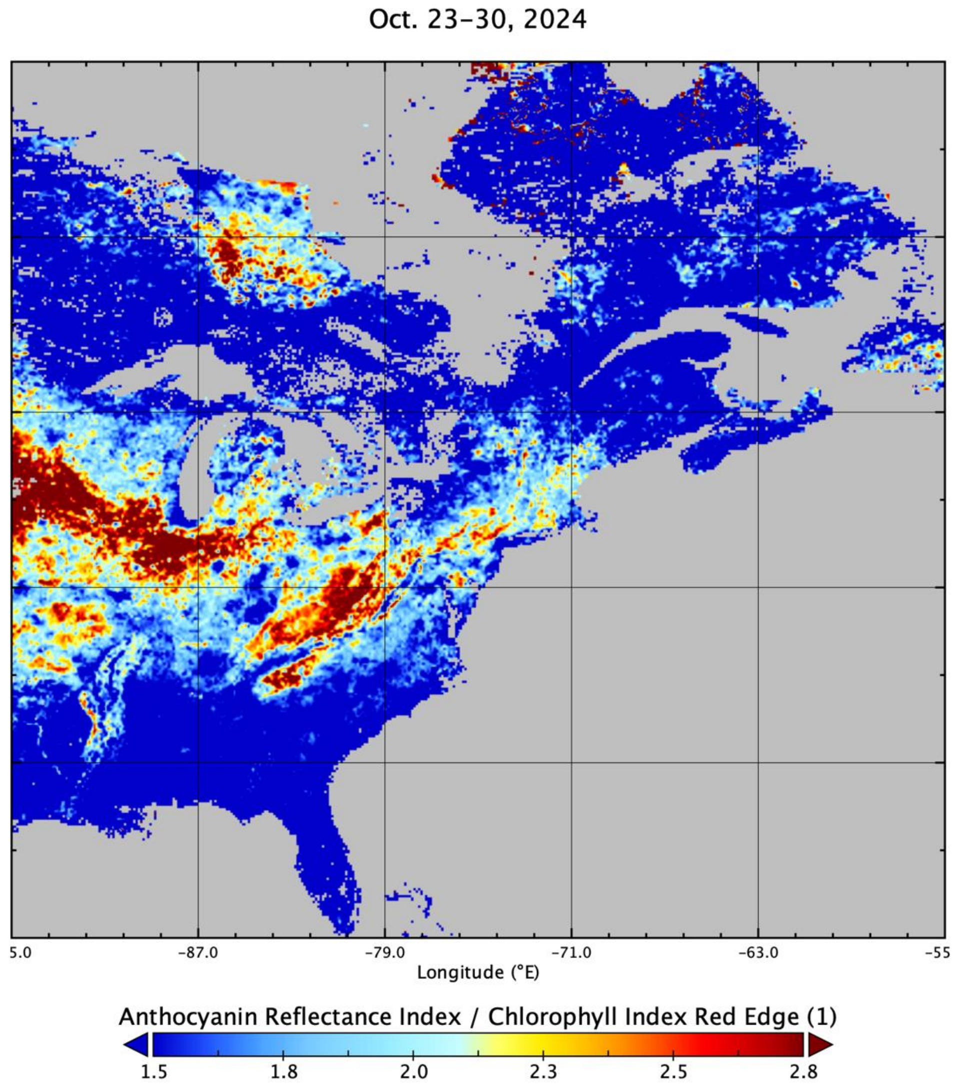
Autumnal Tints from PACE

Now fall color has appeared in the southern Appalachian Mountains, while the areas in the north are now past peak color



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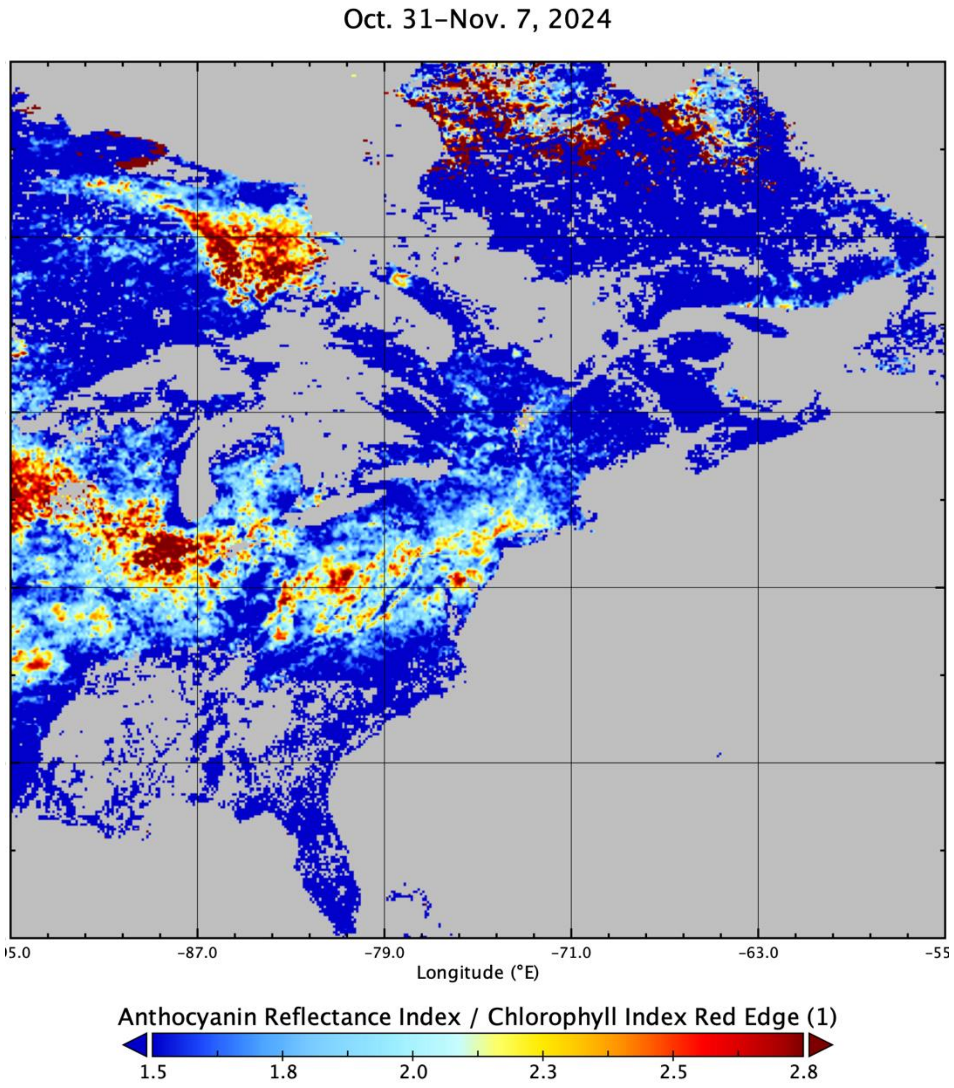

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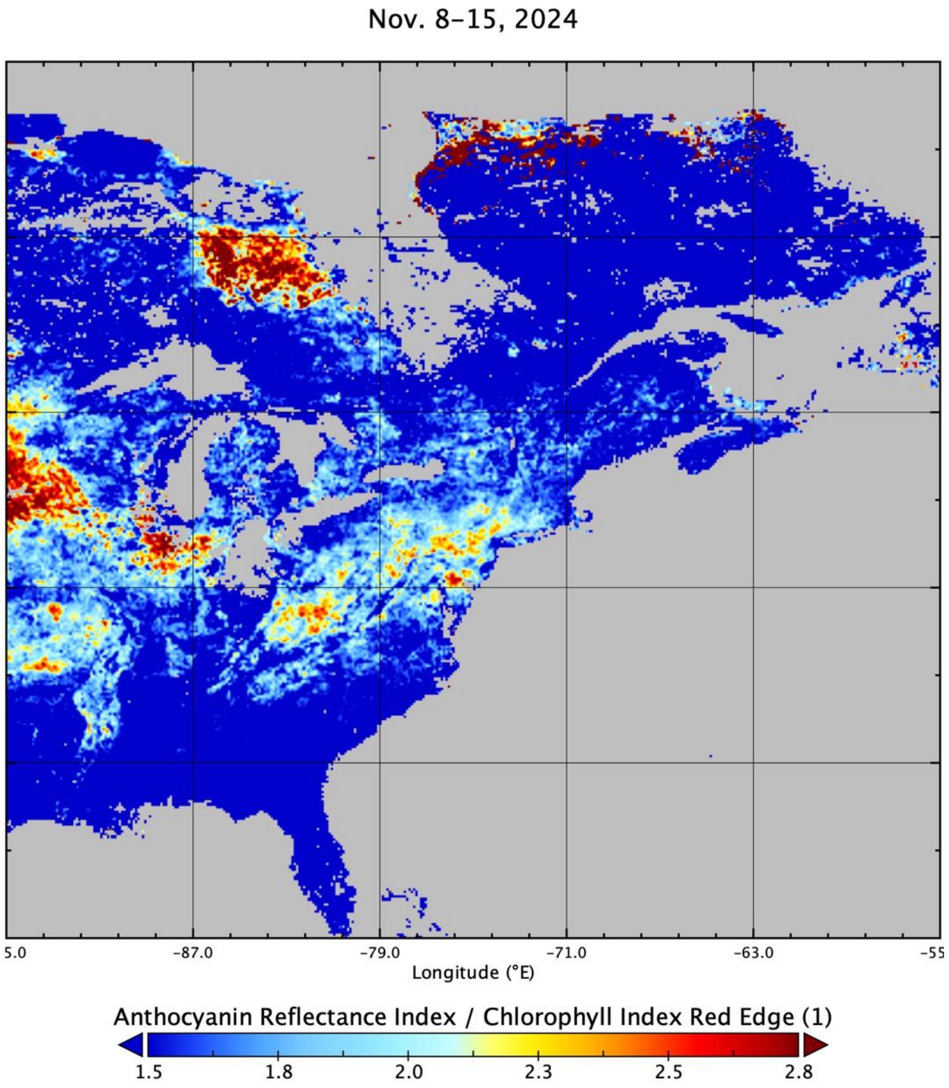

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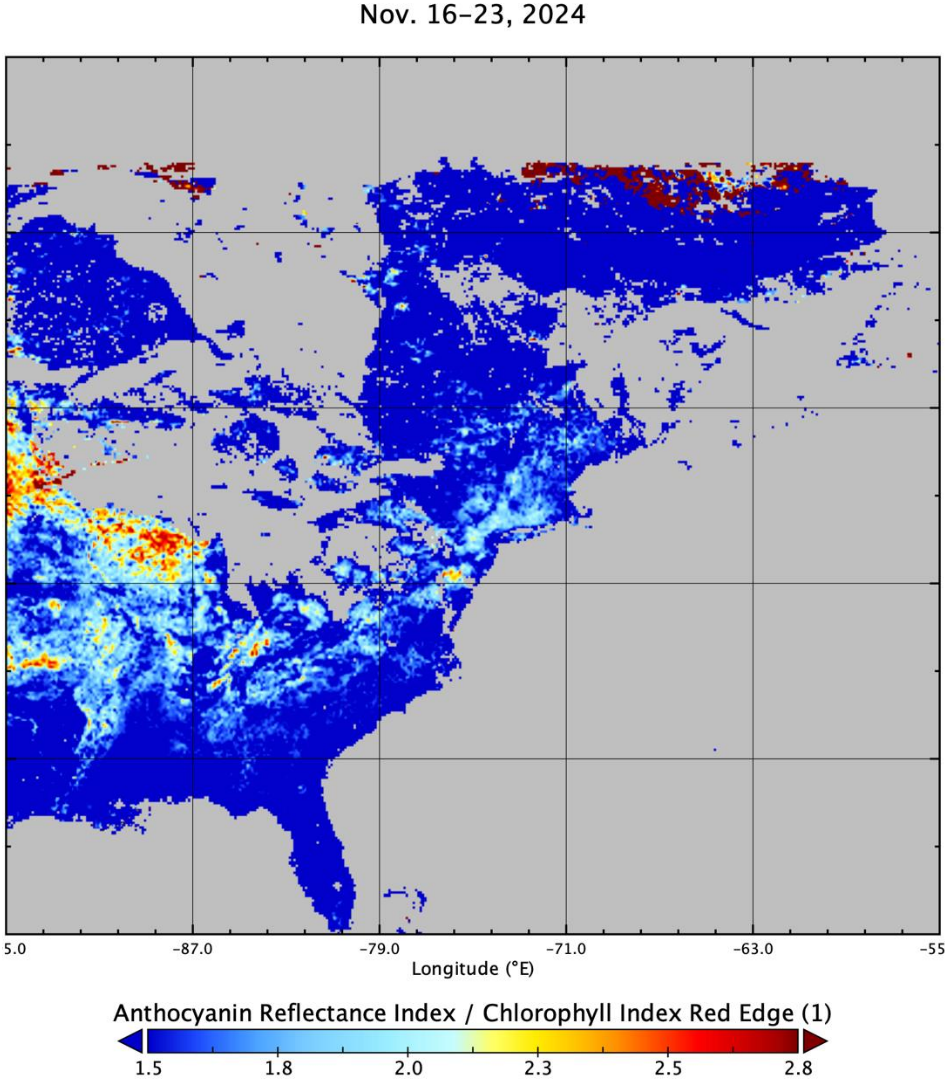

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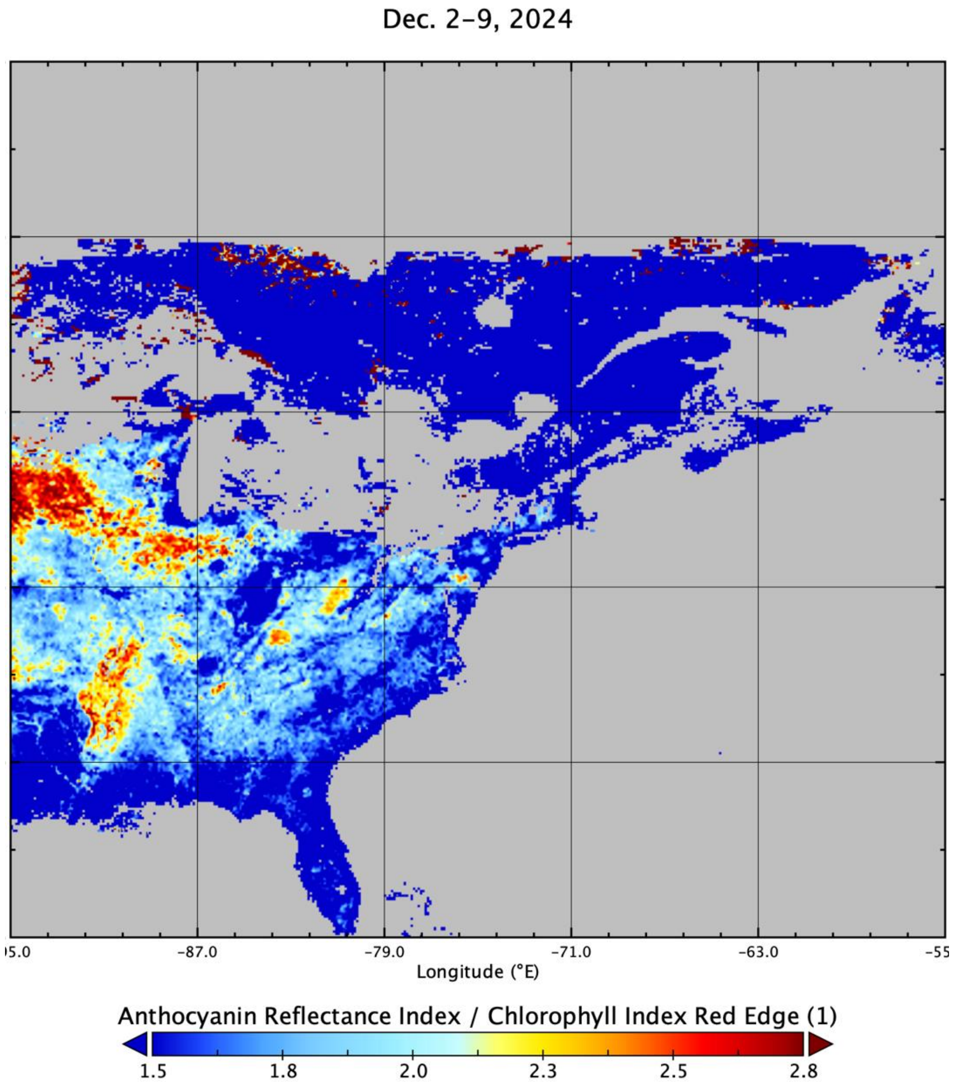

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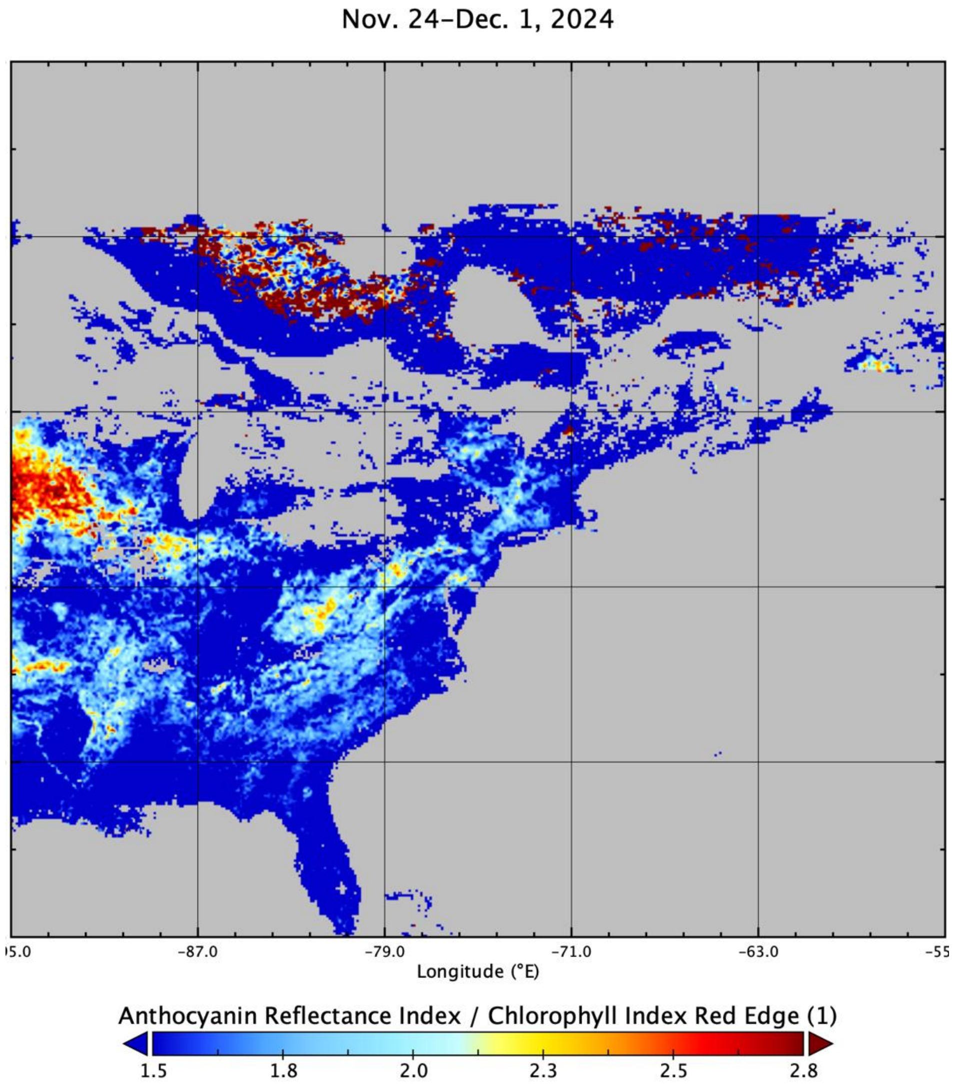

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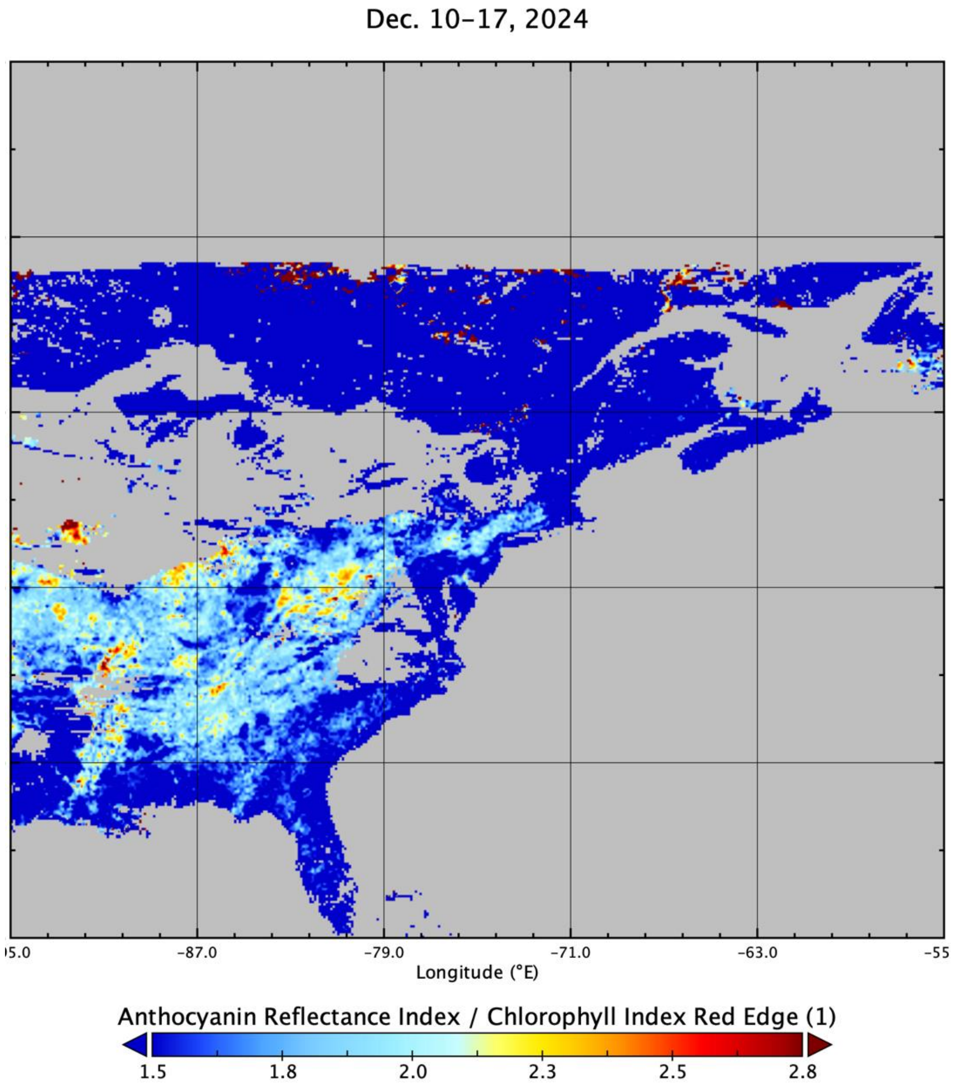

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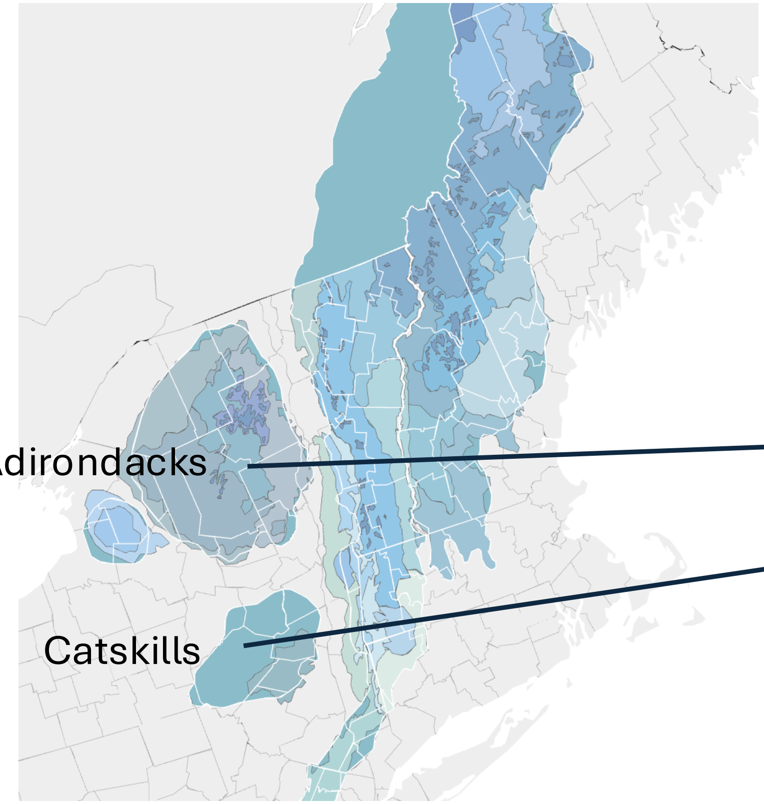
Autumnal Tints from PACE - Ecoregions

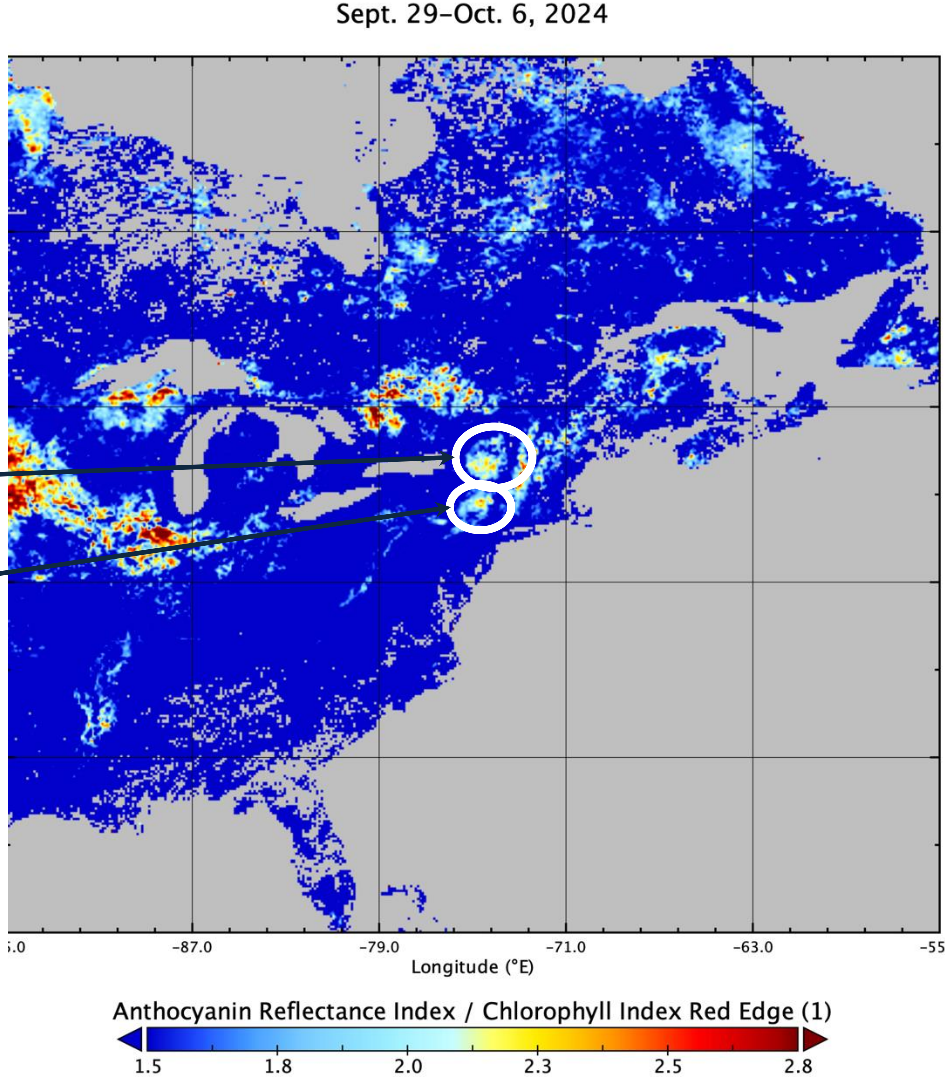
Onset of fall color clearly indicates specific ecoregions

Central Adirondacks

Catskills



https://bplant.org/regions.php



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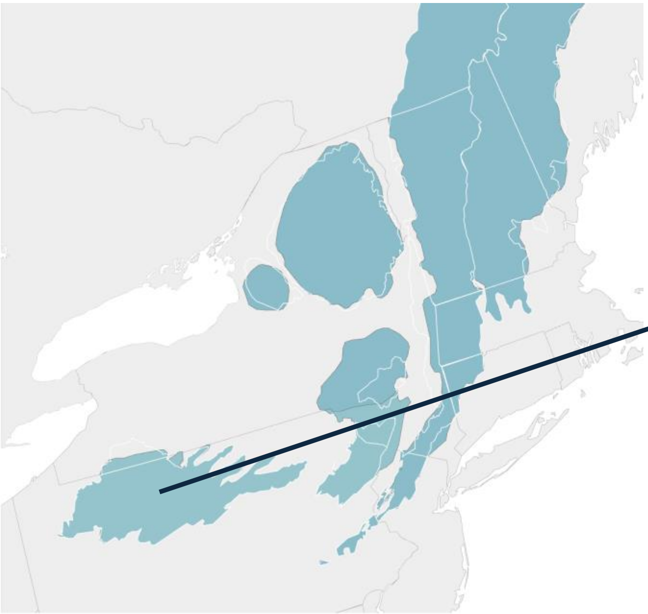
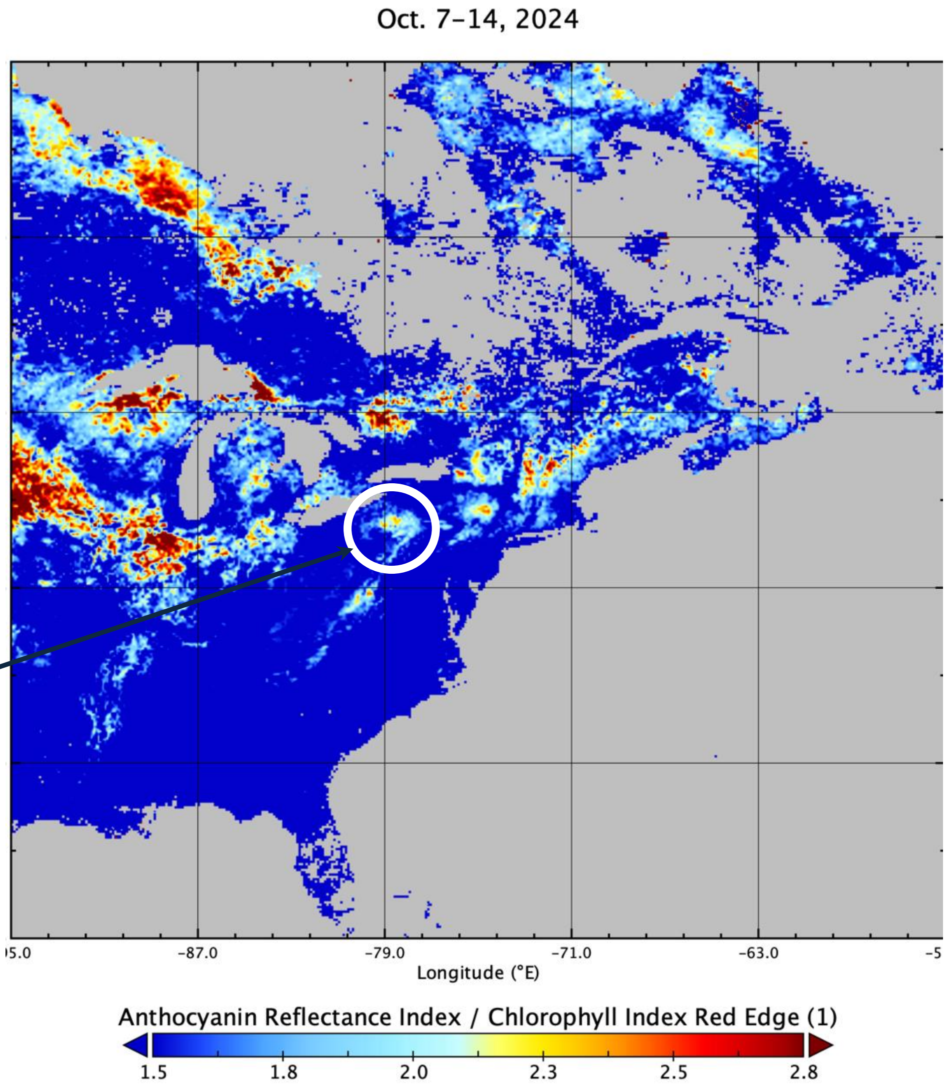


Unglaciated High
Allegheny Plateau



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Autumnal Tints from PACE - Ecoregions

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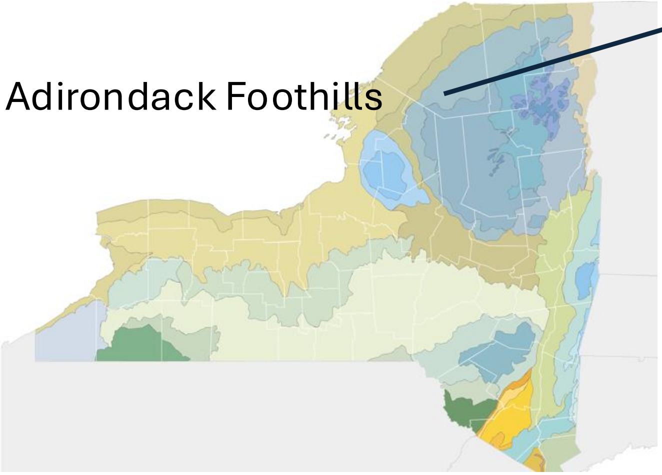
Hudson Bay Lowlands

(actually taiga and wetlands, not deciduous, but still shows a strong anthocyanin signal)

Adirondack Foothills



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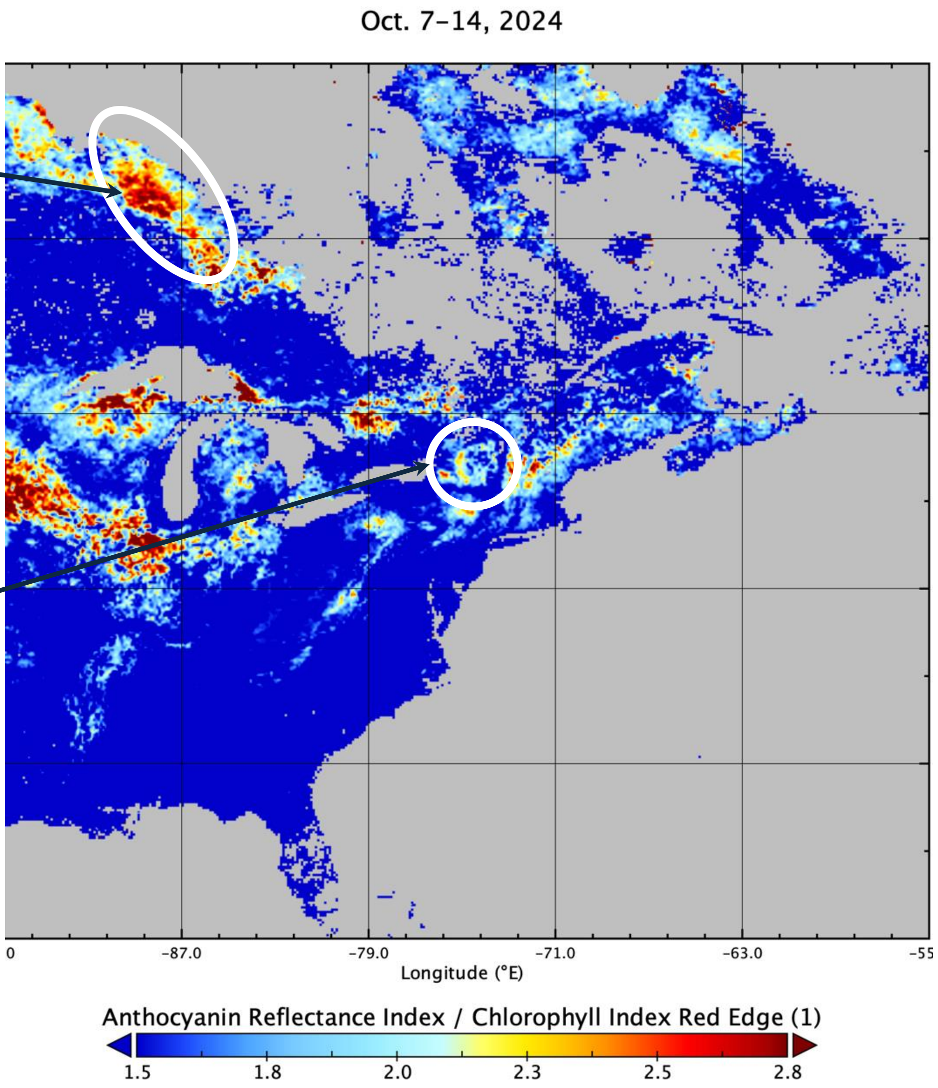

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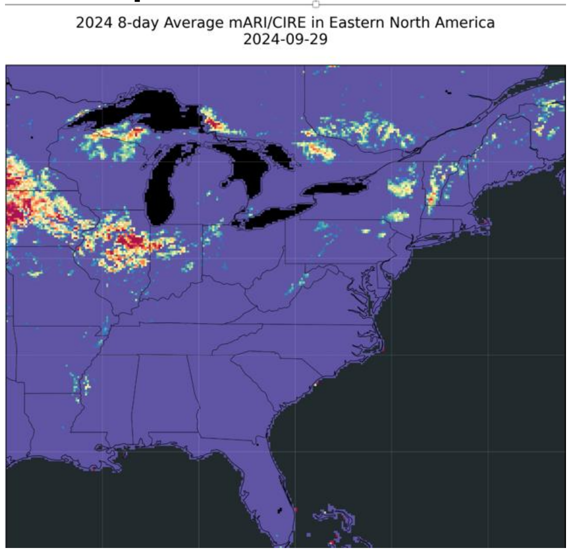
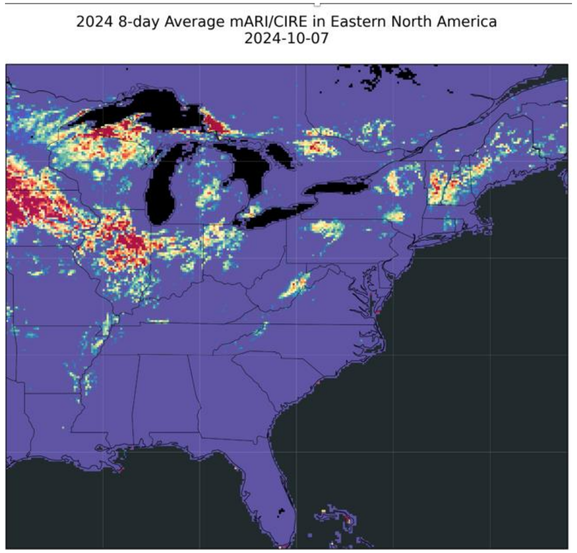
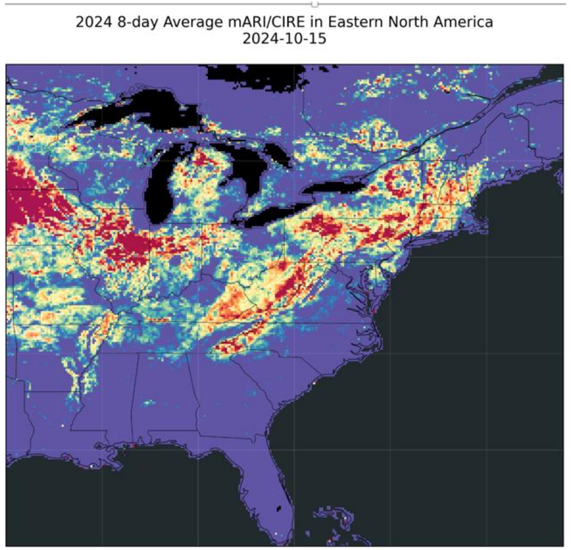
Autumnal Tints from PACE – 2024 and 2025

	Sept. 29-Oct. 6	Oct. 7-14	Oct. 15-22

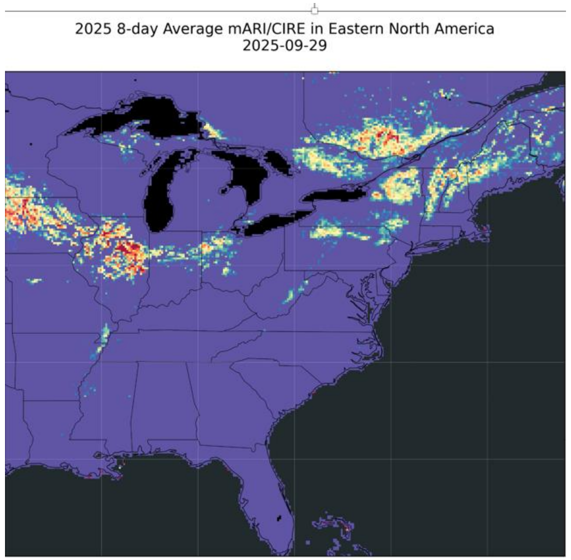
2024

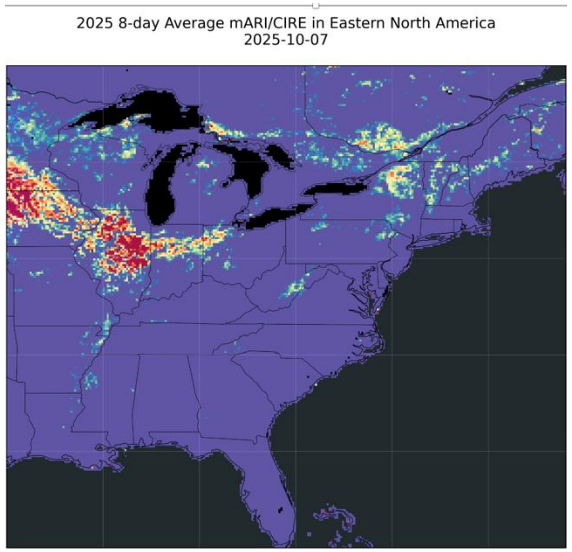


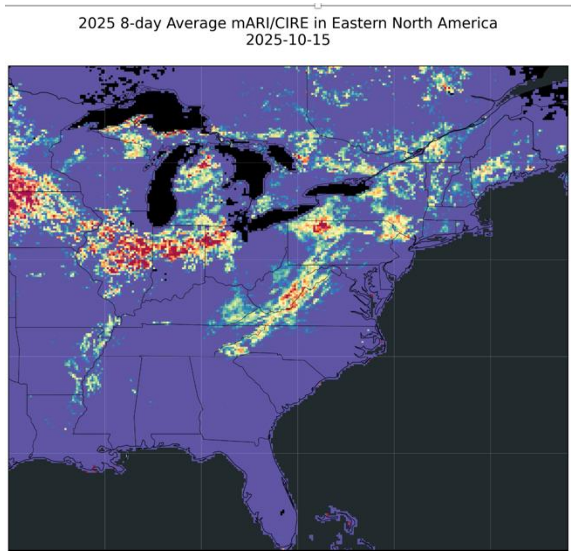




2025







Earlier start of fall colors in north in 2025

Earlier fall colors in Appalachian Mountains in 2024

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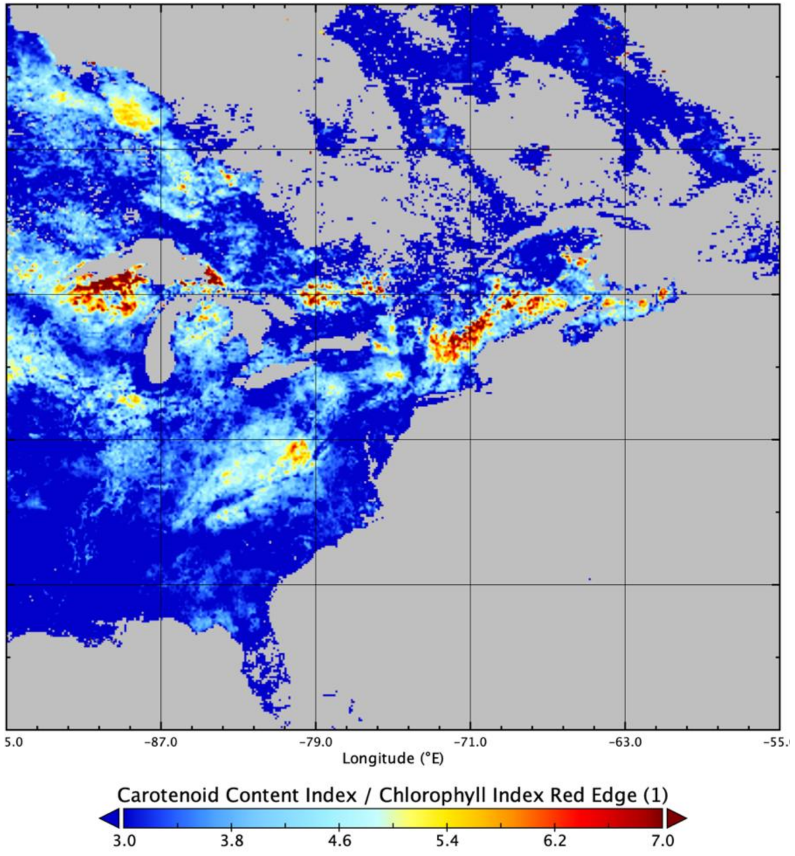
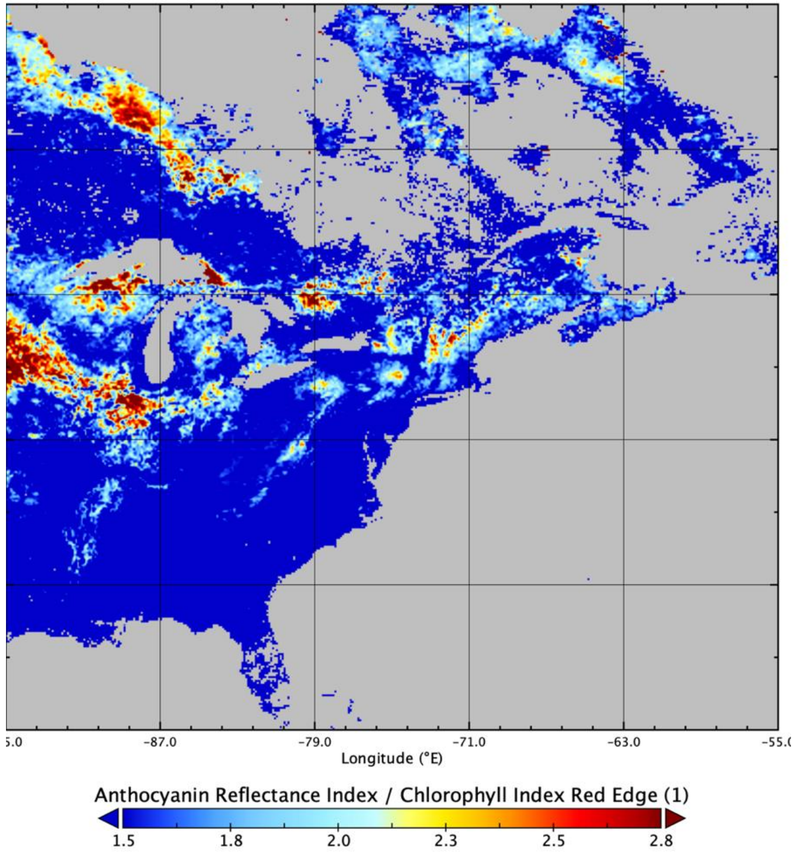
Autumnal Tints from PACE – Carotenoids (yellow) and Anthocyanins (red)

Carotenoid Index /Chlorophyll Index
Oct. 7-14, 2024



Anthocyanin Index /Chlorophyll Index
Oct. 7-14, 2024



Different spatial patterns emerge when viewing different pigments
Differences may be due to species and/or weather conditions
For Car/Cire, Corn belt is less prominent, color change in southern Appalachians is stronger

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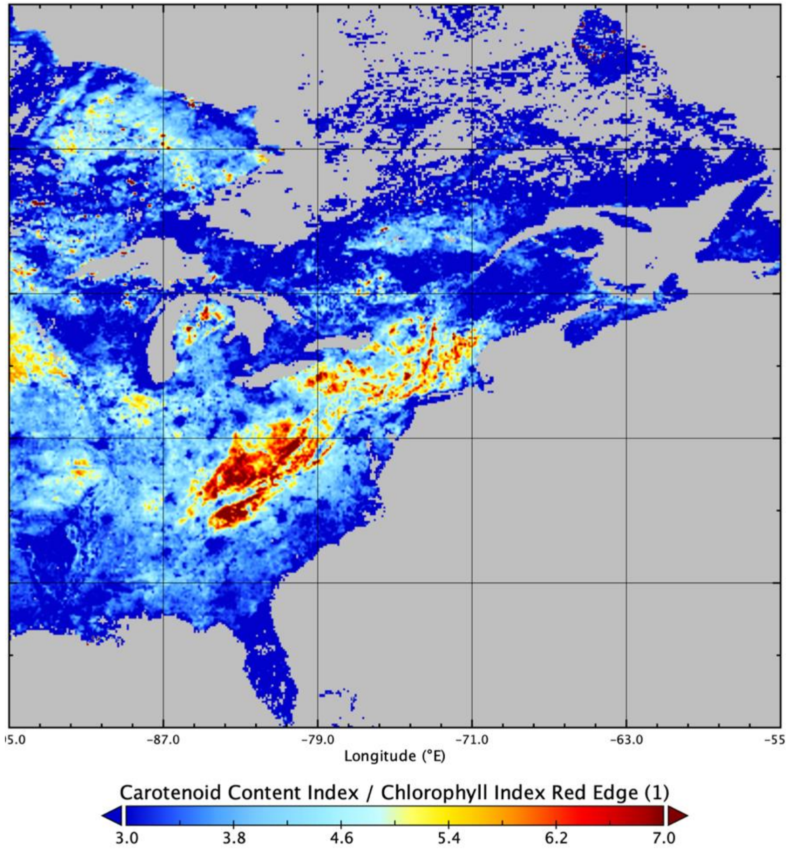
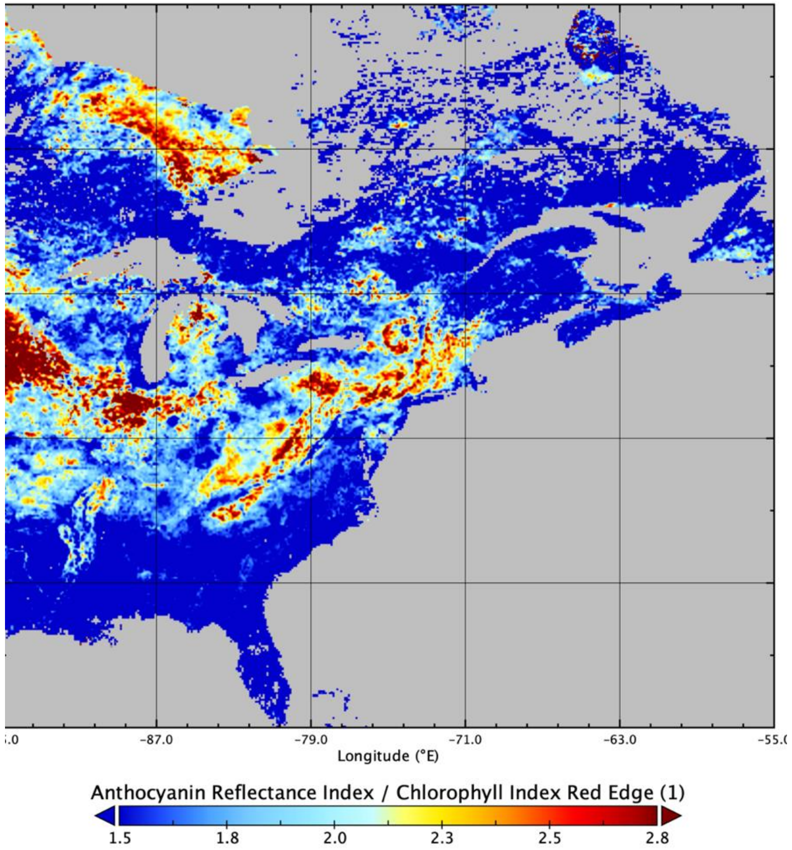


Anthocyanin Index /Chlorophyll Index Oct. 15-22, 2024



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Conclusions

The changing colors of autumn leaves in deciduous forests of eastern North America represent an important phenological process which is affected by climate change

The onset of fall foliage impacts:

- Seasonal productivity – the breakdown of chlorophyll in leaves ends photosynthetic activity
- Ecosystem carbon and water balance – the end of photosynthetic activity (CO_2 flux) and transpiration (moisture flux)
- Albedo and energy balance – changes in leaf color alters absorption of sunlight
- Economy from tourism – viewing fall foliage is a significant activity worth on the order of $billions annually

PACE's repeated hyperspectral observations provide a new view of seasonal fall foliage change based on pigment indices

- This is a more direct and physiologically based approach than used in previous remote sensing studies based on greenness indices
  - It provides a better temporal description of leaf color change
- Spatial and temporal patterns of PACE derived fall colors clearly identify responses in specific ecoregions

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Acknowledgements

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