Autumnal Tints: Observing Fall Foliage with PACE

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Introduction

- 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

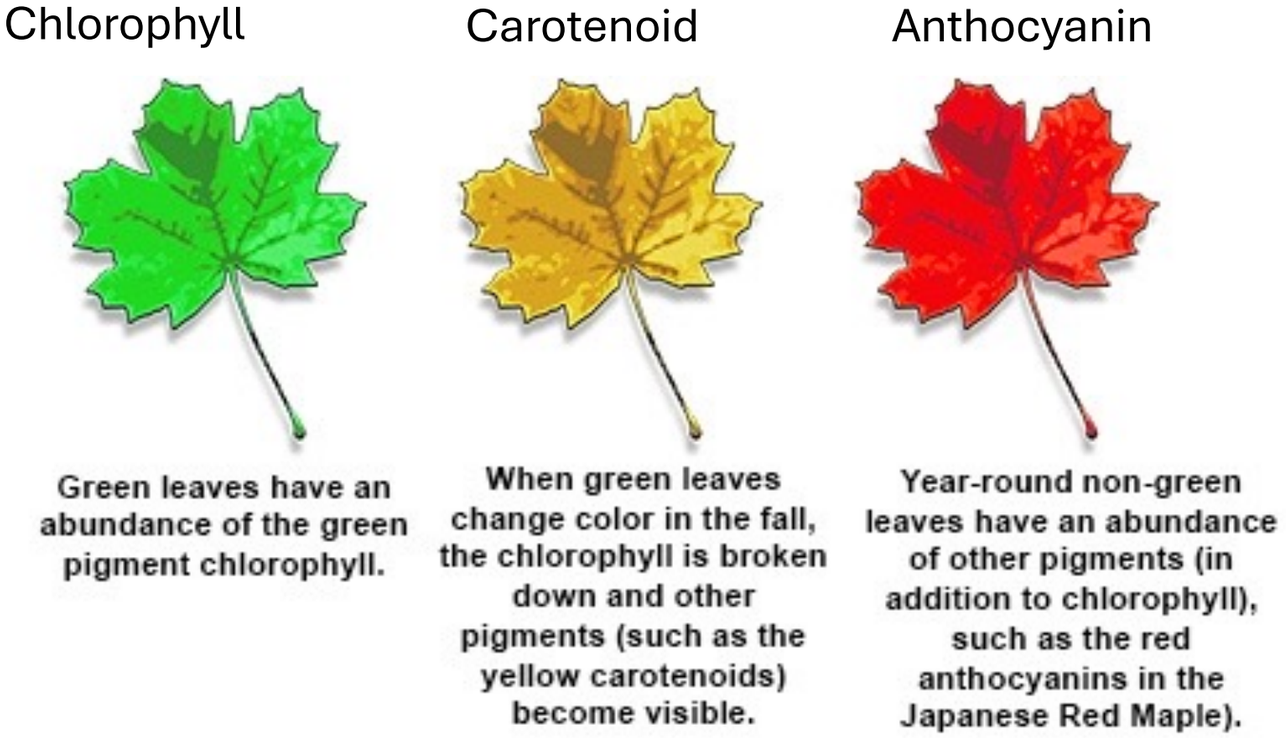
Leaf Pigments

Autumn leaf senescence 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.



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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

CIRE - Chlorophyll Index Red Edge - canopy chlorophyll content

$CIRE = (\rho 800/\rho 705) - 1)$

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

$mARI = [(1/\rho 550) - (1/\rho 705)] * \rho 800$

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

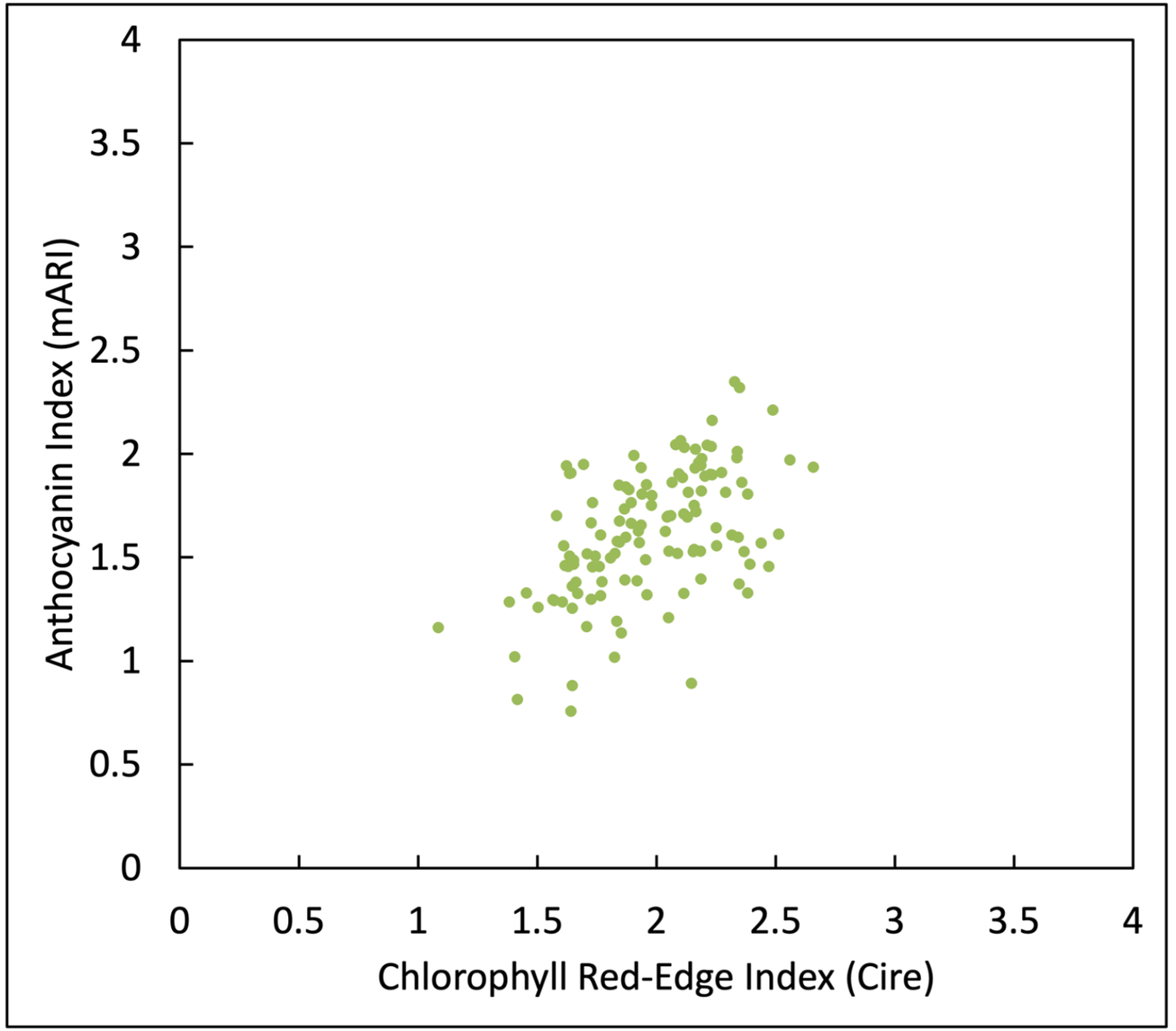
$Car = [(1/\rho 495) - (1/\rho 705)] * \rho 800$

Deciduous Forest Autumn Pigment Index Dynamics

Points for forested area in southeastern West Virginia (37.8-38.8° N, 79.8-89.8° W)
8-day averages, ~6x11 km mapped cells, ~100 cells

September 13-20, 2024

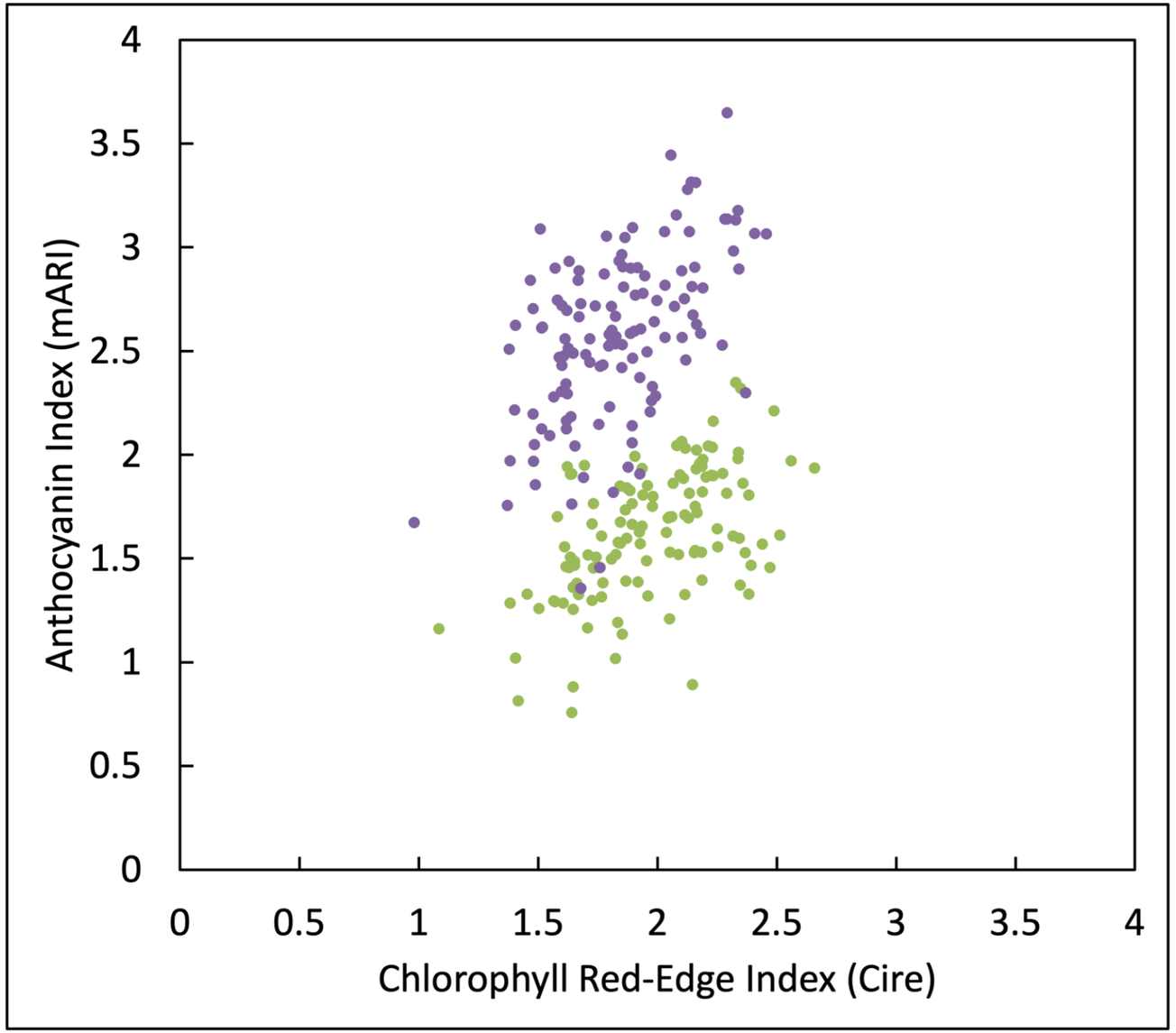
Late summer, high Chlorophyll, low Anthocyanin



Deciduous Forest Autumn Pigment Index Dynamics

September 21-28, 2024

Early fall,
high Chlorophyll,
increased Anthocyanin



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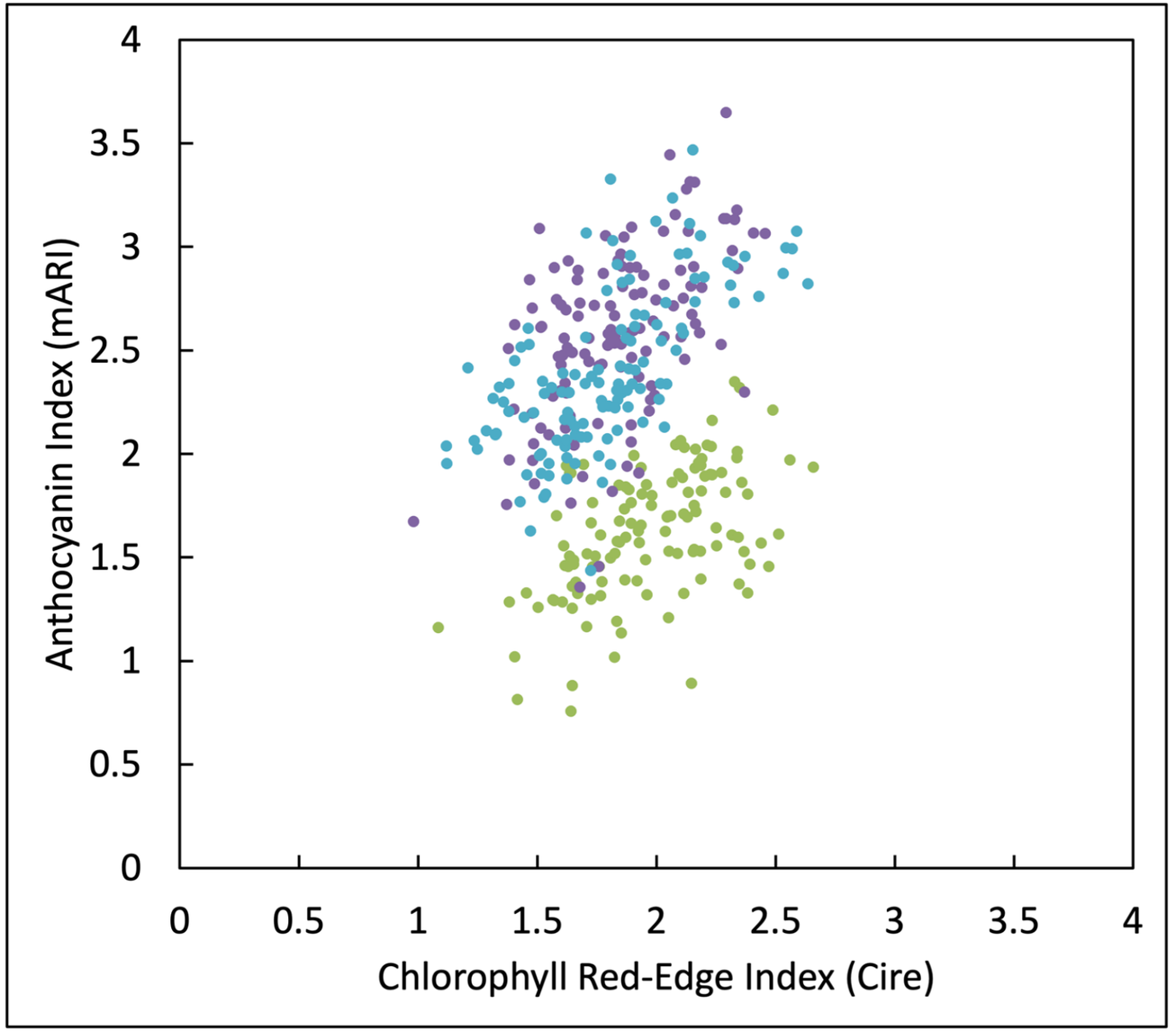
Deciduous Forest Autumn Pigment Index Dynamics

September 29-October 6, 2024

Early fall,
high Chlorophyll,
increased Anthocyanin



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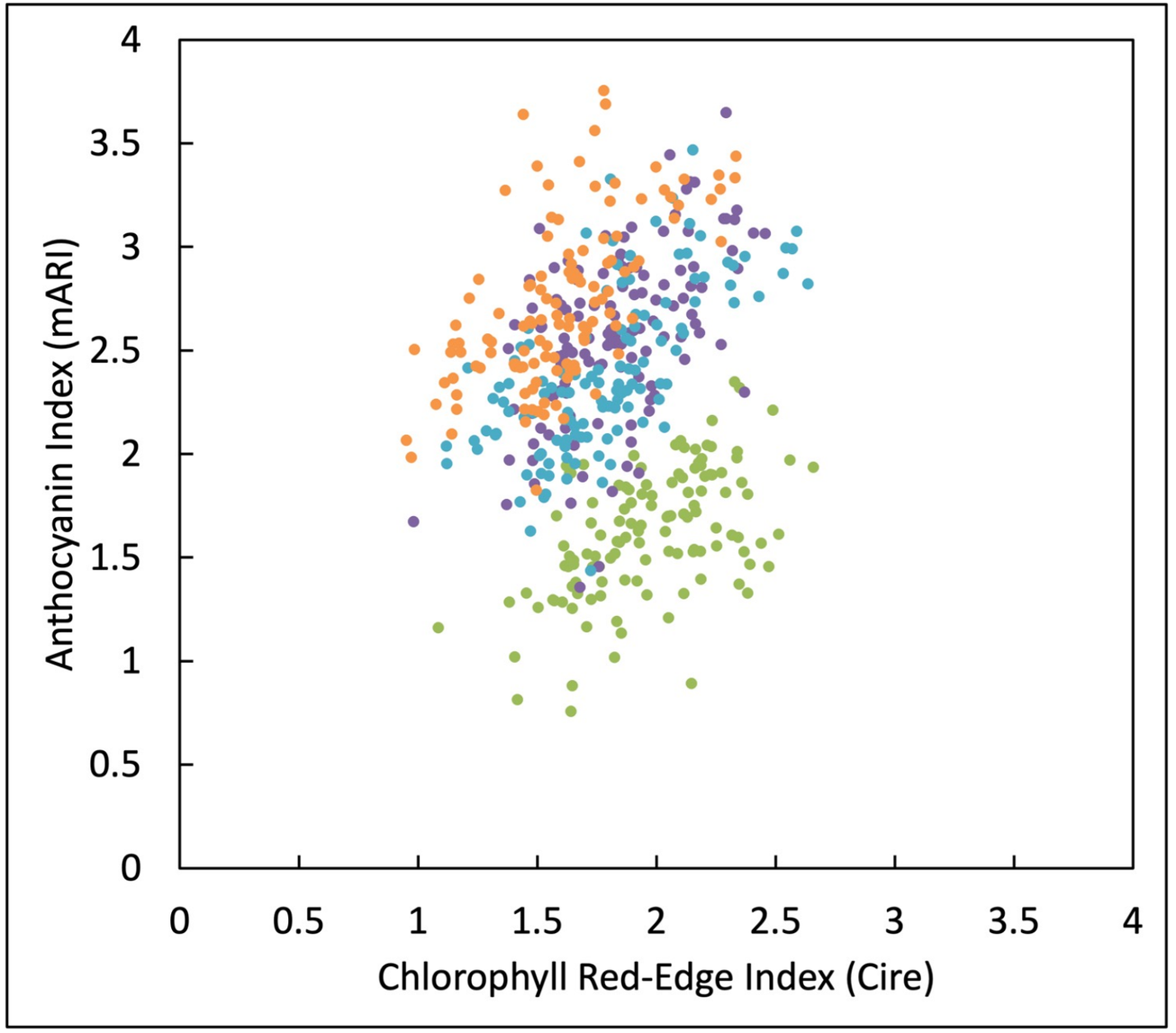
Deciduous Forest Autumn Pigment Index Dynamics

October 7-14, 2024

Fall,
decreasing Chlorophyll,
high Anthocyanin



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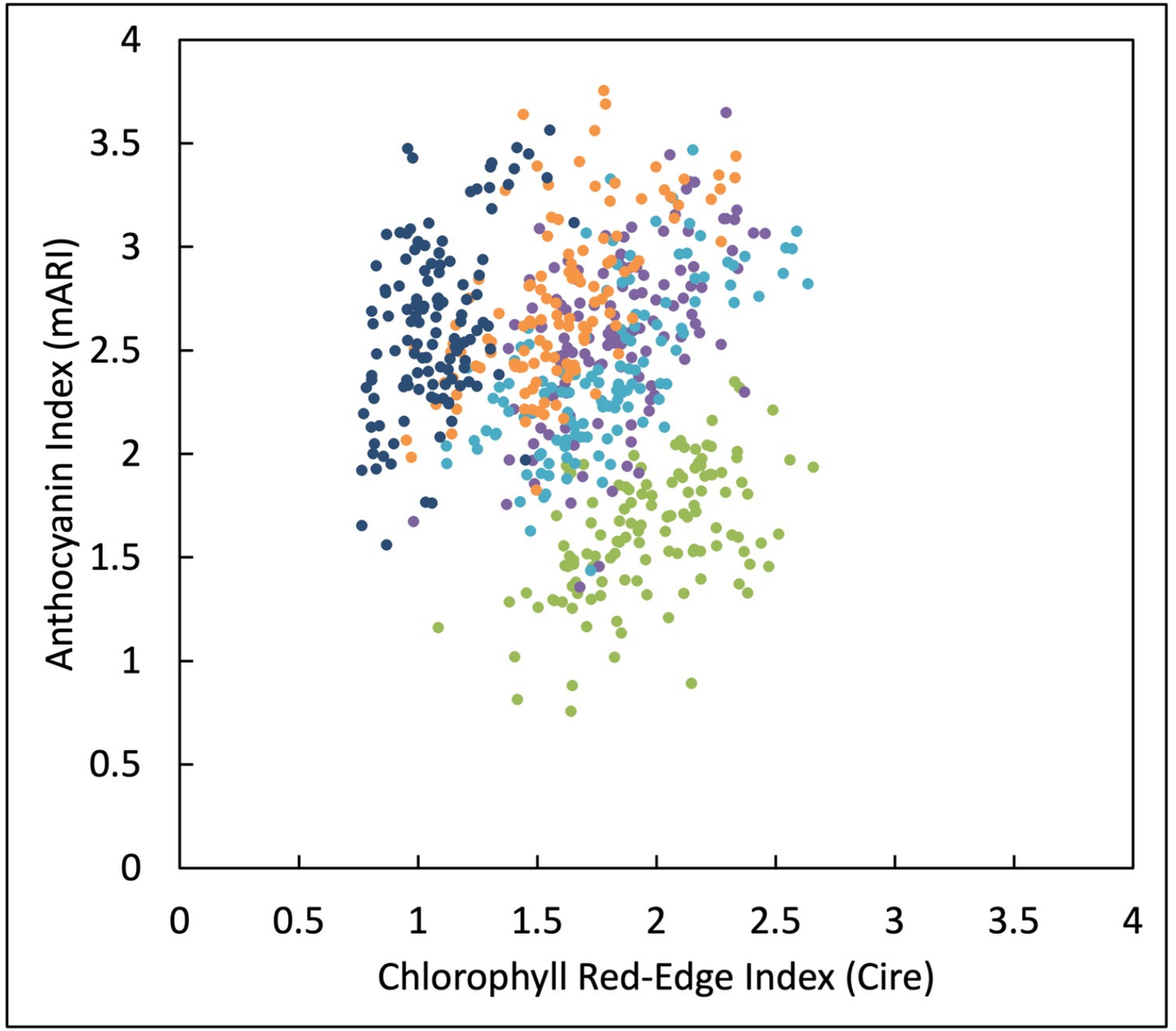
Deciduous Forest Autumn Pigment Index Dynamics

October 15-22, 2024

Fall,
decreasing Chlorophyll,
high Anthocyanin



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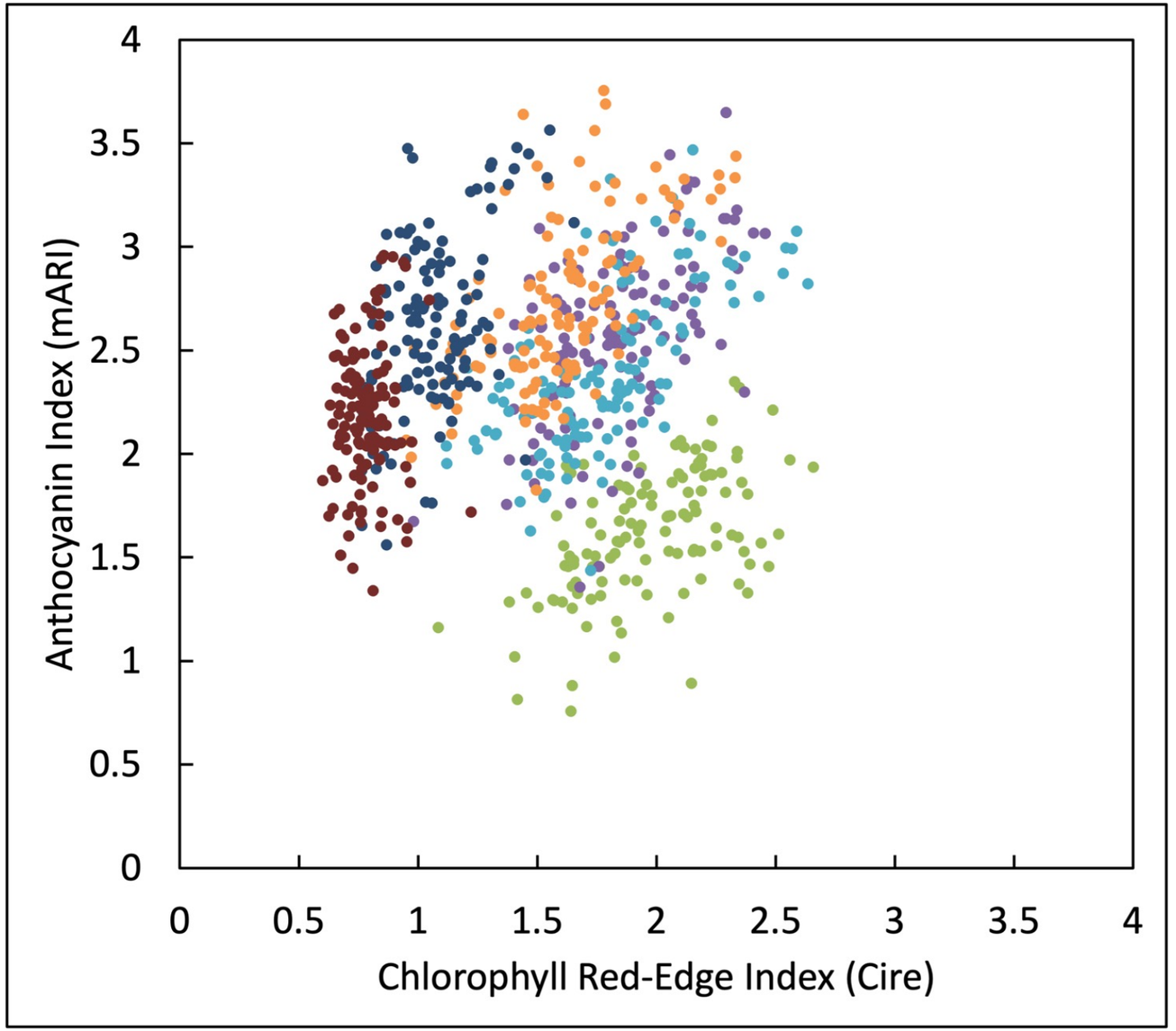
Deciduous Forest Autumn Pigment Index Dynamics

October 23-30, 2024

Late Fall,
low Chlorophyll,
decreasing Anthocyanin



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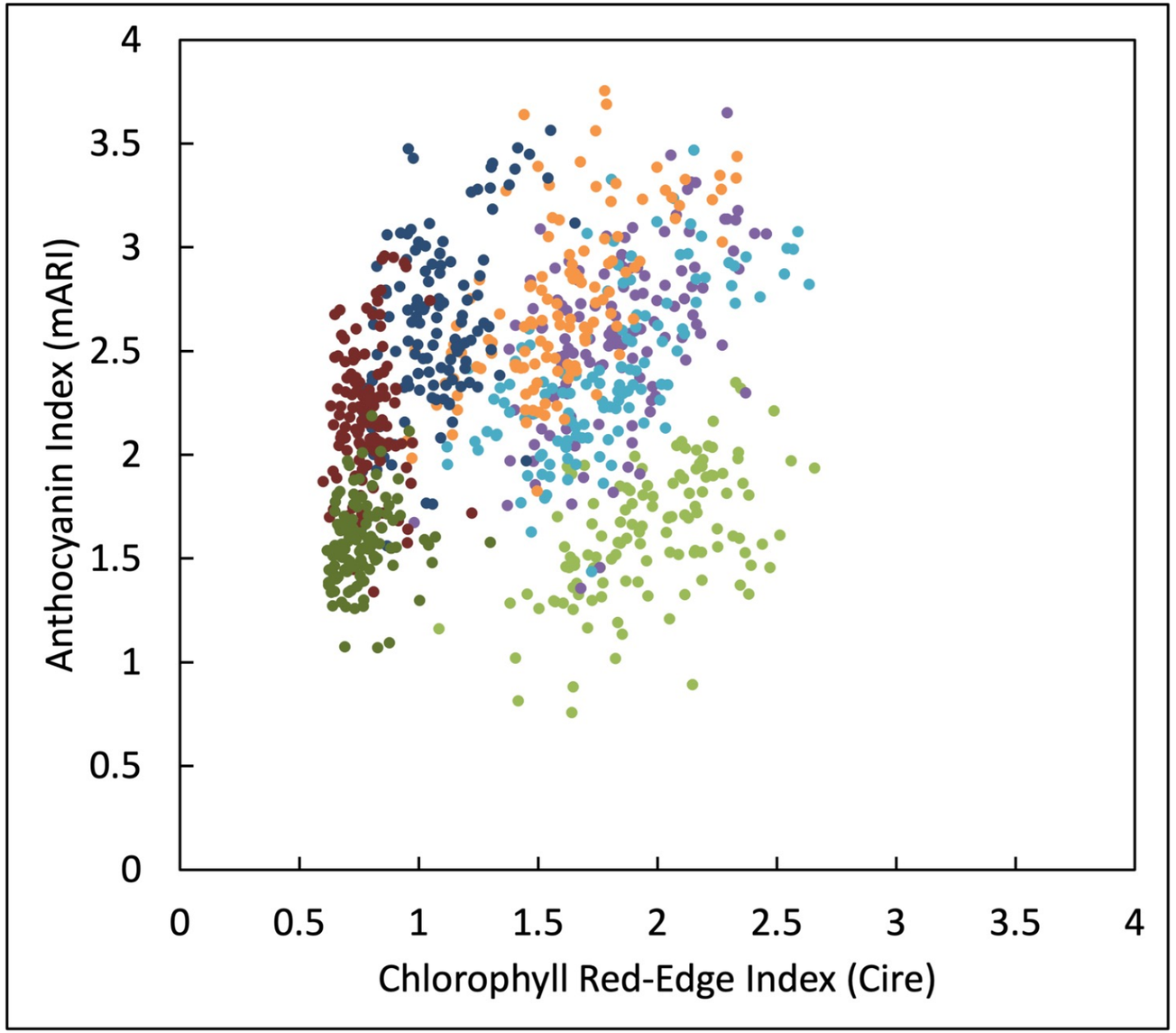
Deciduous Forest Autumn Pigment Index Dynamics

October 31-November 7, 2024

Late Fall,
low Chlorophyll,
decreasing Anthocyanin



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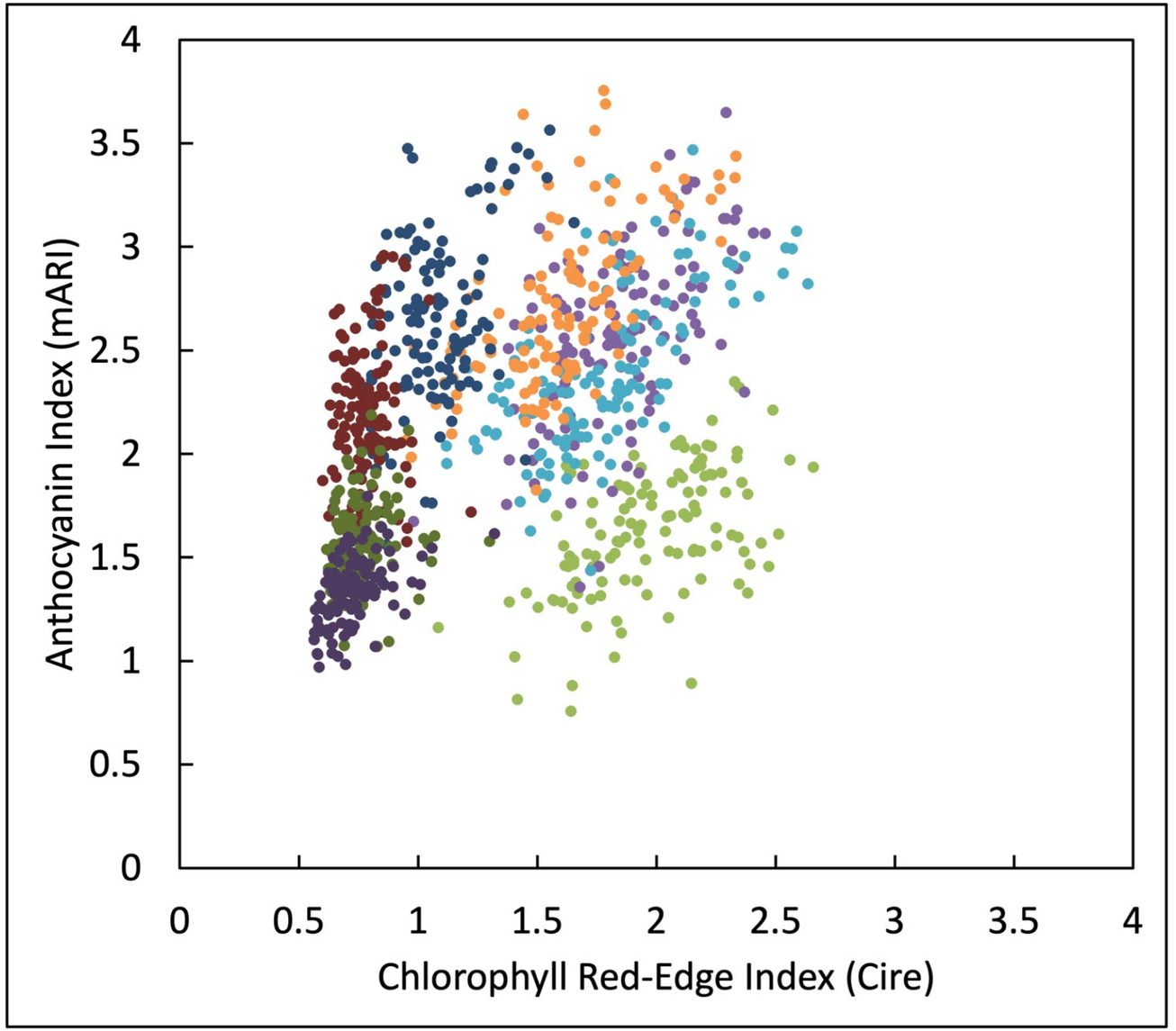
Deciduous Forest Autumn Pigment Index Dynamics

November 8-15, 2024

Late Fall,
low Chlorophyll,
low Anthocyanin



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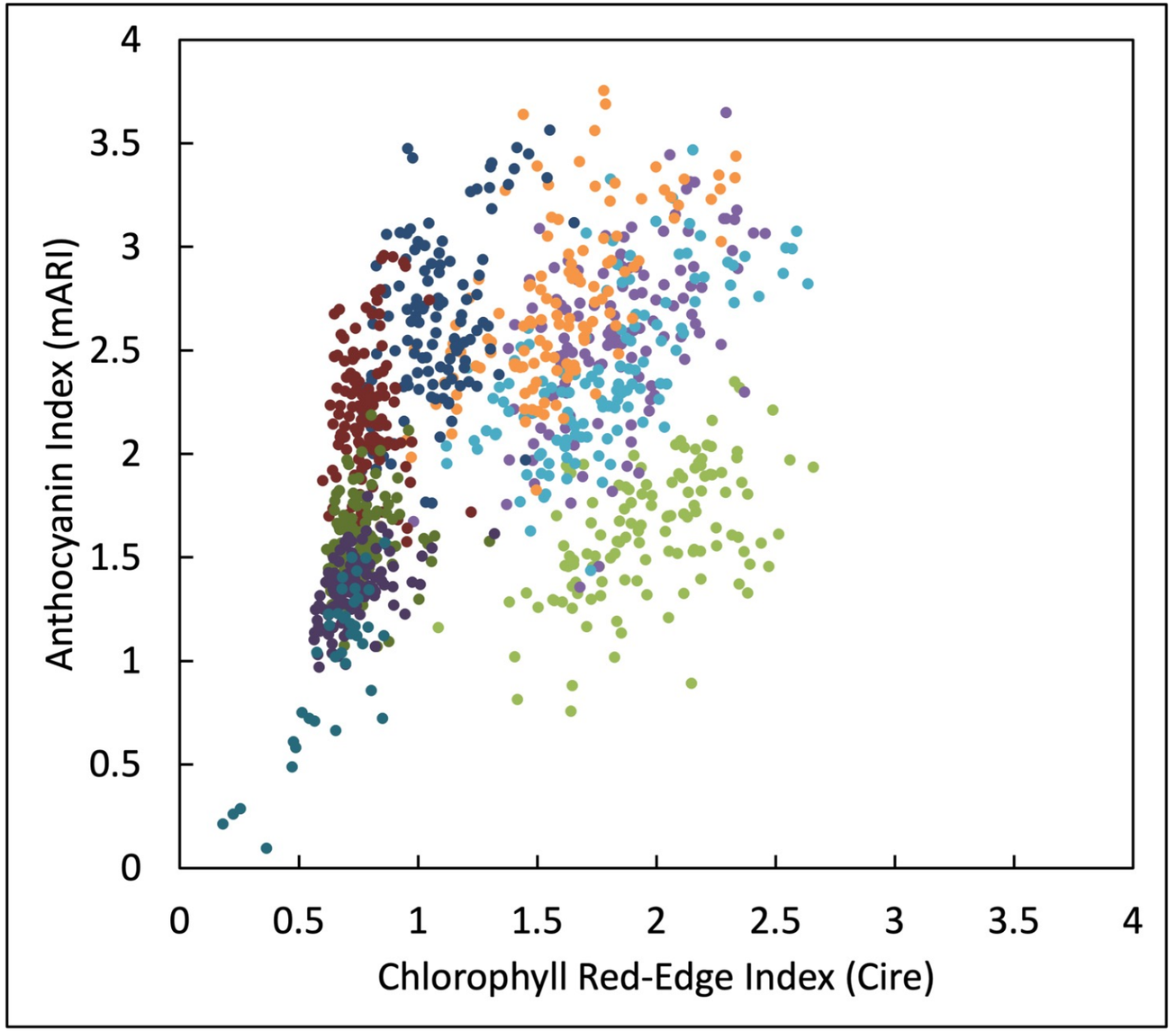
Deciduous Forest Autumn Pigment Index Dynamics

November 16-23, 2024

Late Fall,
low Chlorophyll,
low Anthocyanin



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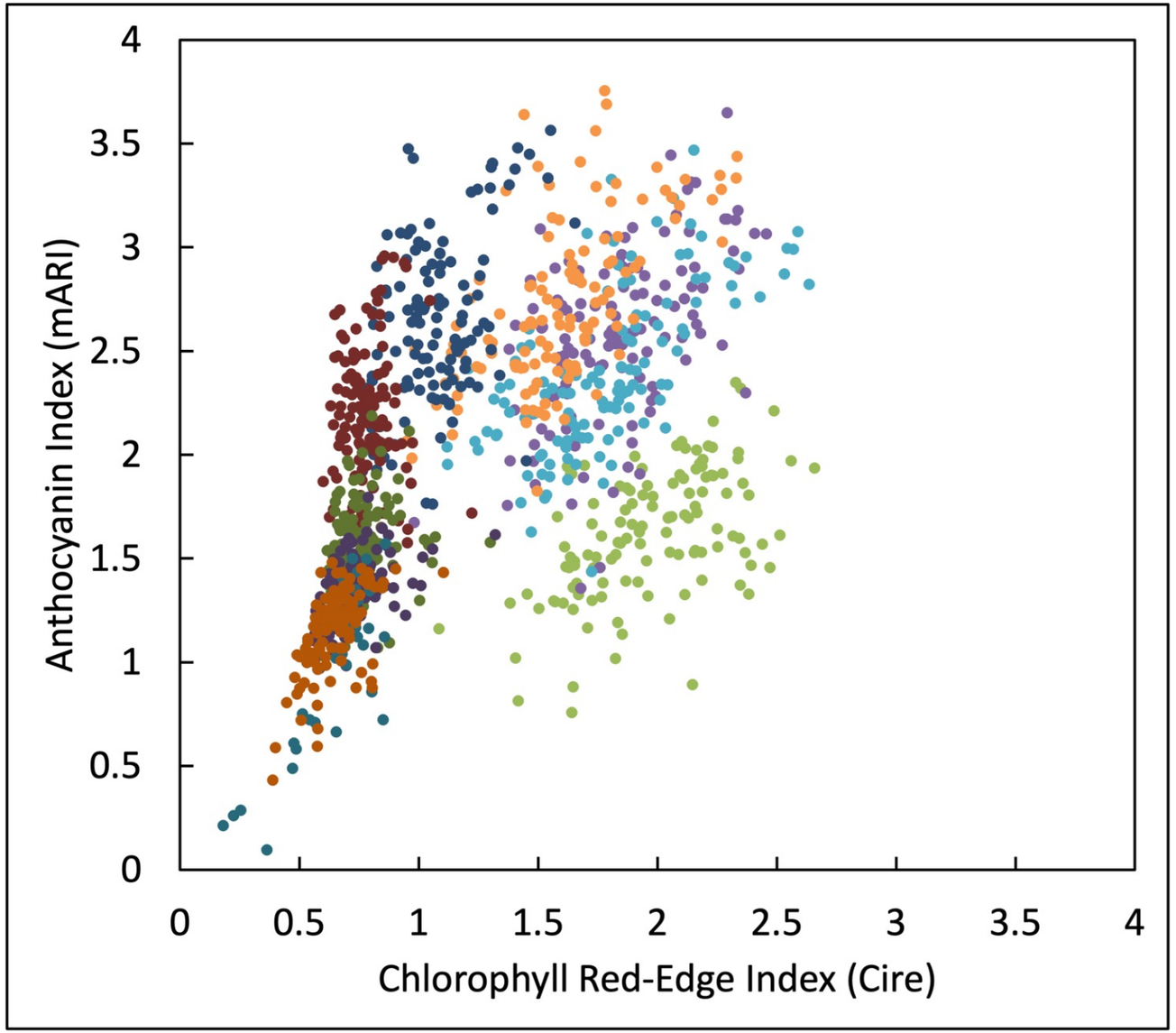
Deciduous Forest Autumn Pigment Index Dynamics

November 24-December 1, 2024

Late Fall,
low Chlorophyll,
low Anthocyanin



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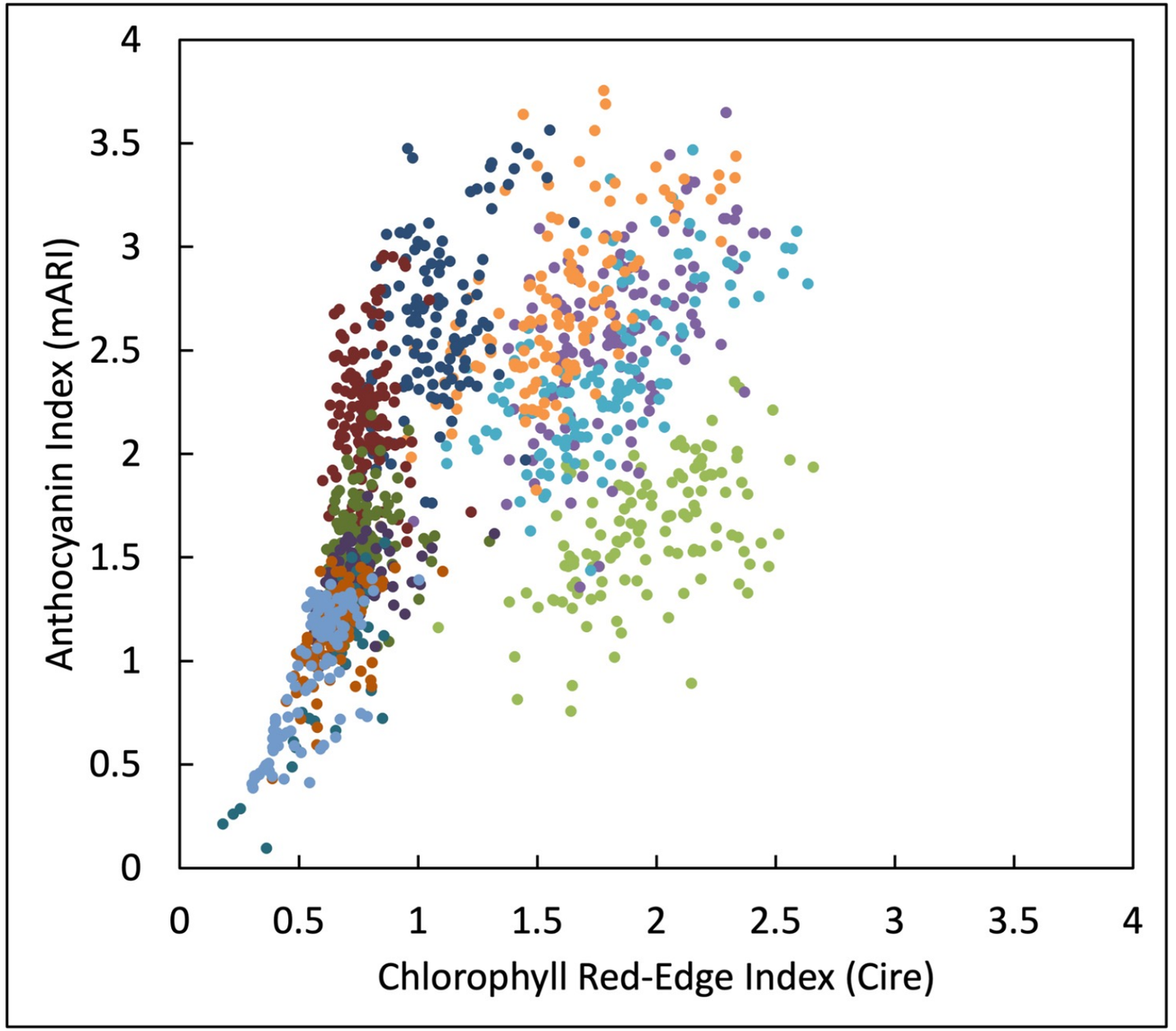
Deciduous Forest Autumn Pigment Index Dynamics

December 2-9, 2024

Late Fall,
low Chlorophyll,
low Anthocyanin



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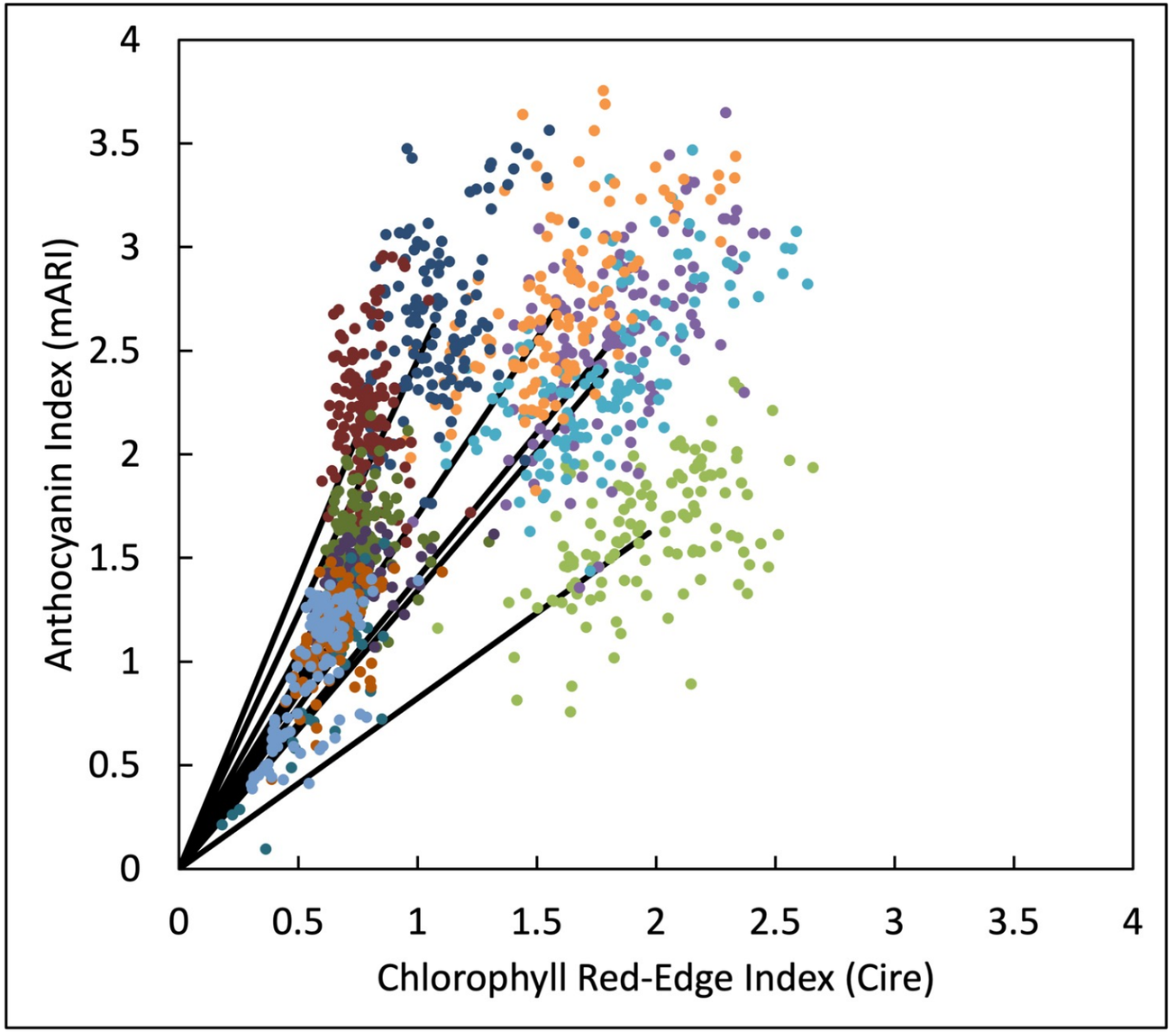
Deciduous Forest Autumn Pigment Index Dynamics

The changes in both Chlorophyll and Anthocyanin indices are combined by calculating their ratio (mARI/Cire)

Since the indices are driven by canopy leaf area and leaf pigment content, taking the ratio minimizes the effect of varying leaf area and highlights variation in relative leaf pigment pools



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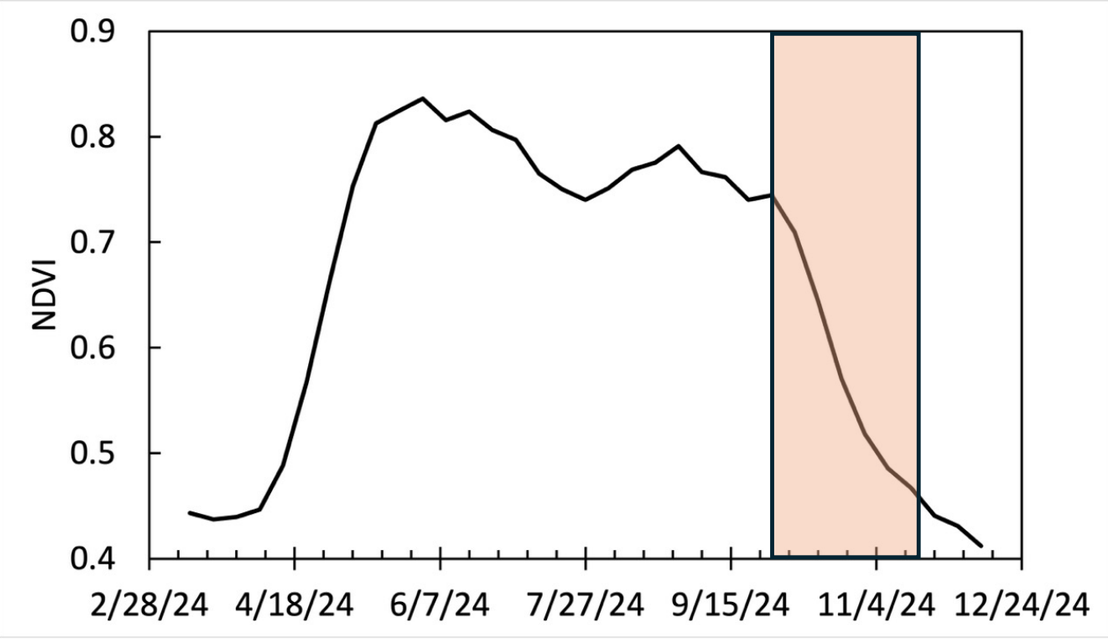
Introduction

- 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

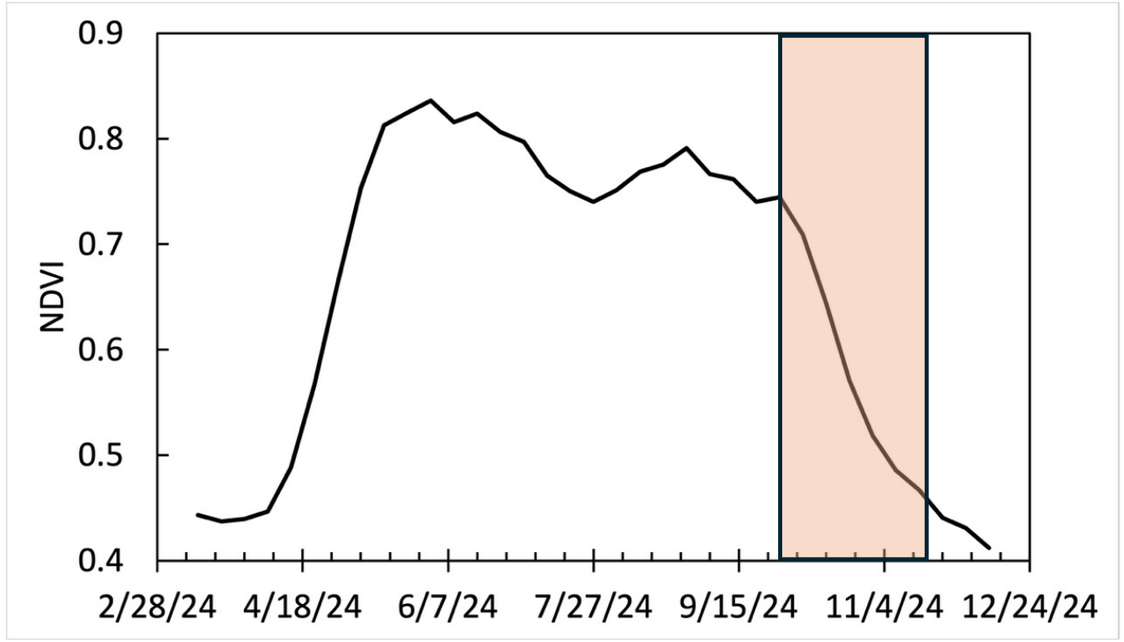


Typical Deciduous forest NDVI seasonal curve, leaf color change occurs some time in the orange shaded area during a period of steady decline in NDVI

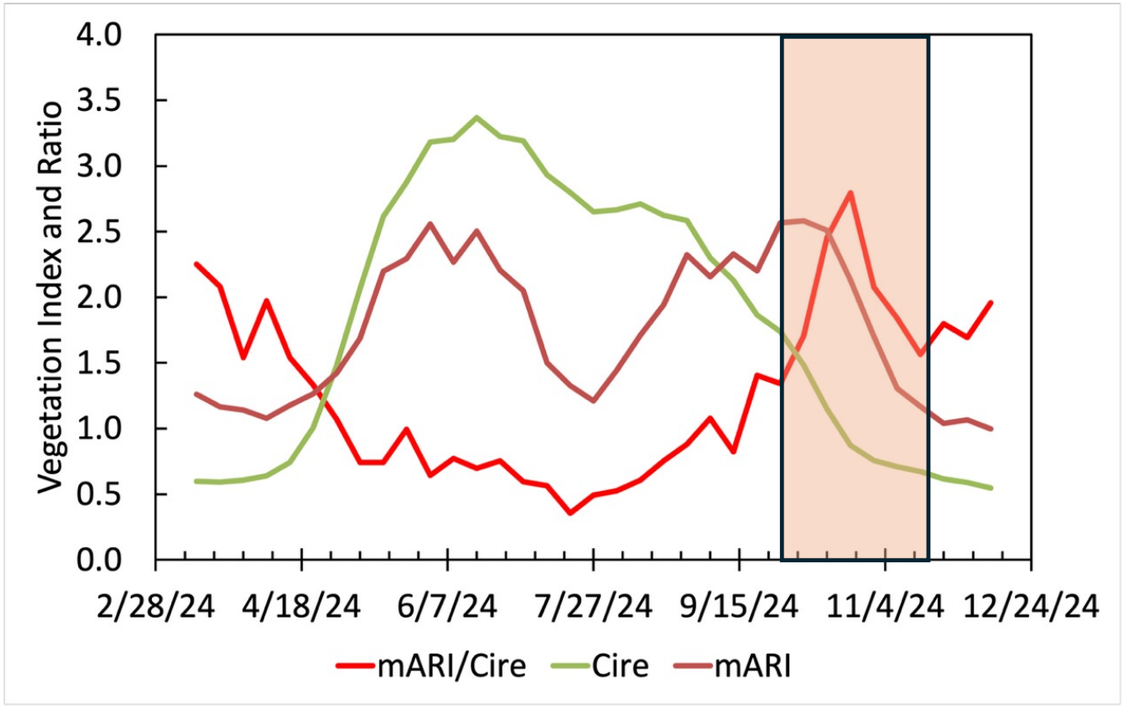
Introduction

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 (red line) shows a clear progression of fall colors



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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?

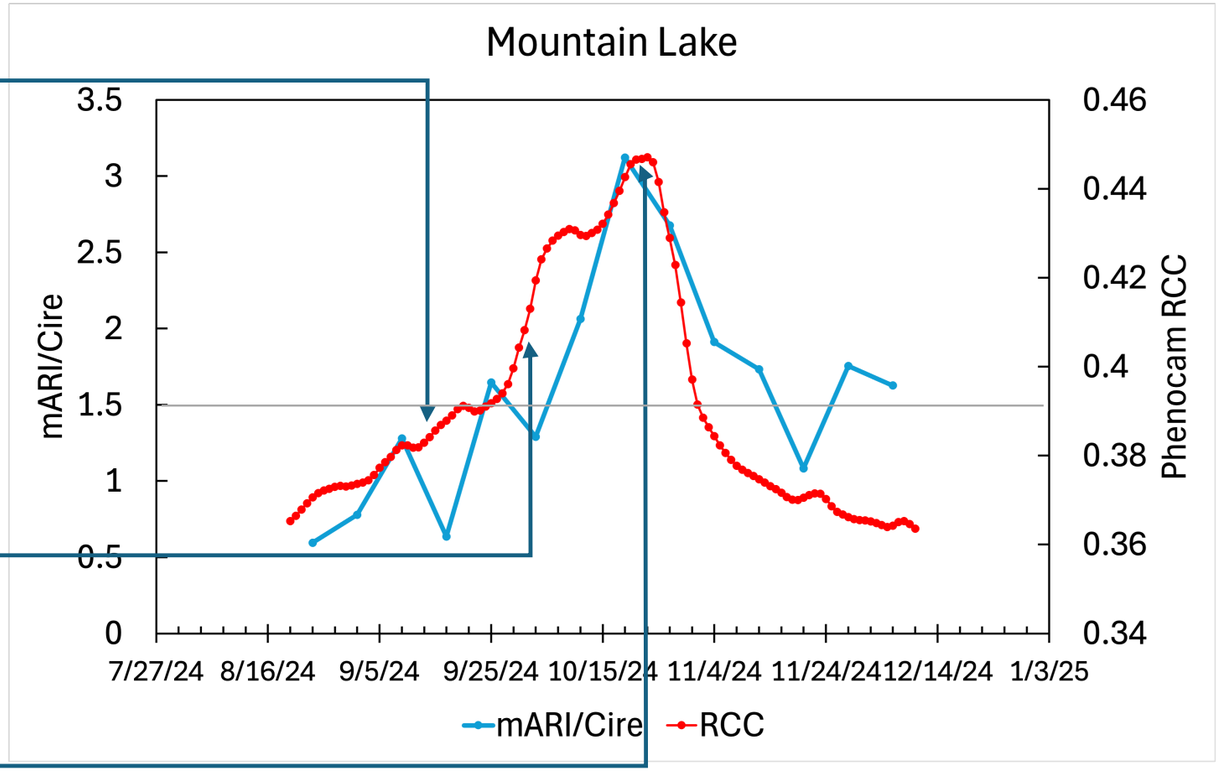
Compare with measurements from phenocams that provide webcam photos of forests

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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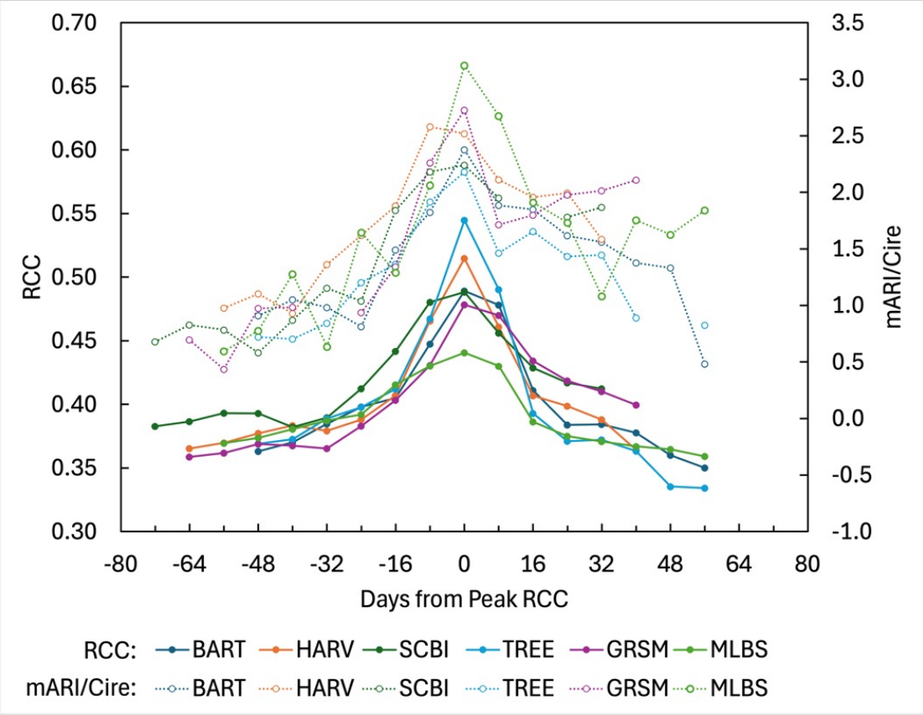
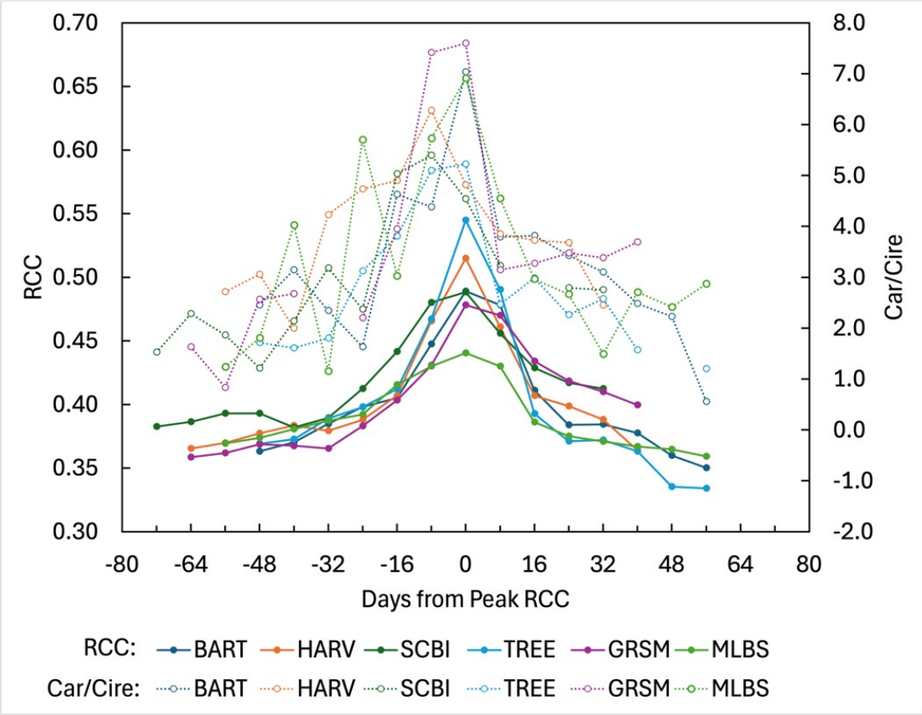
Autumnal Tints from PACE – Comparison with Phenocam Data

Anthocyanin Index / Chlorophyll Index



Carotenoid Index / Chlorophyll Index



Autumn 2024 8-day average 4 km PACE index ratios (mARI/Cire and Car/Cire) 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 (https://www.neonscience.org/data-collection/phenocams)

In these plots the x-axis is the days from peak RCC along with the mARI/Cire and Car/Cire.

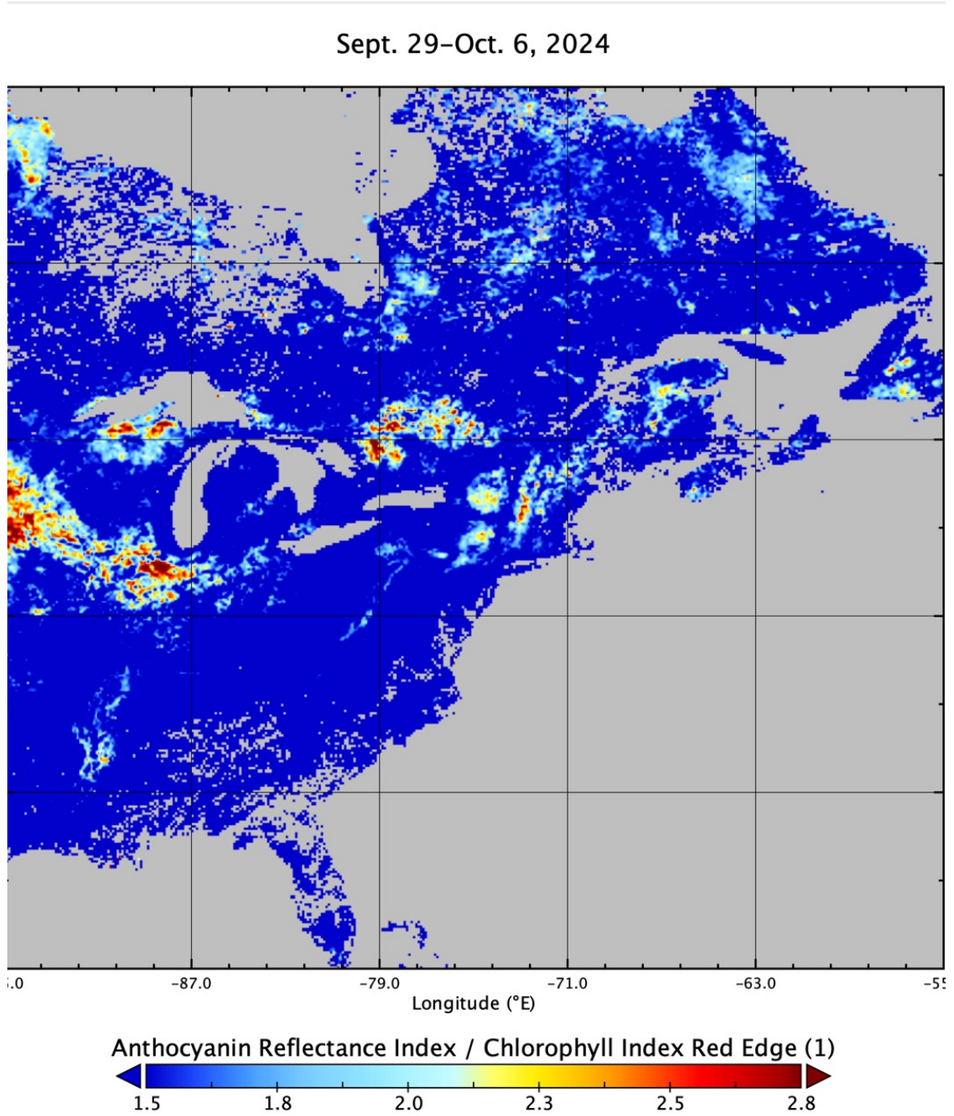
mARI/Cire does a pretty good job of matching the onset of redness and timing of peak RCC, but tends to remain high following the peak.

Car/Cire shows color change earlier than RCC and tends to peak earlier than RCC, but tracks the after-peak drop-off with RCC.

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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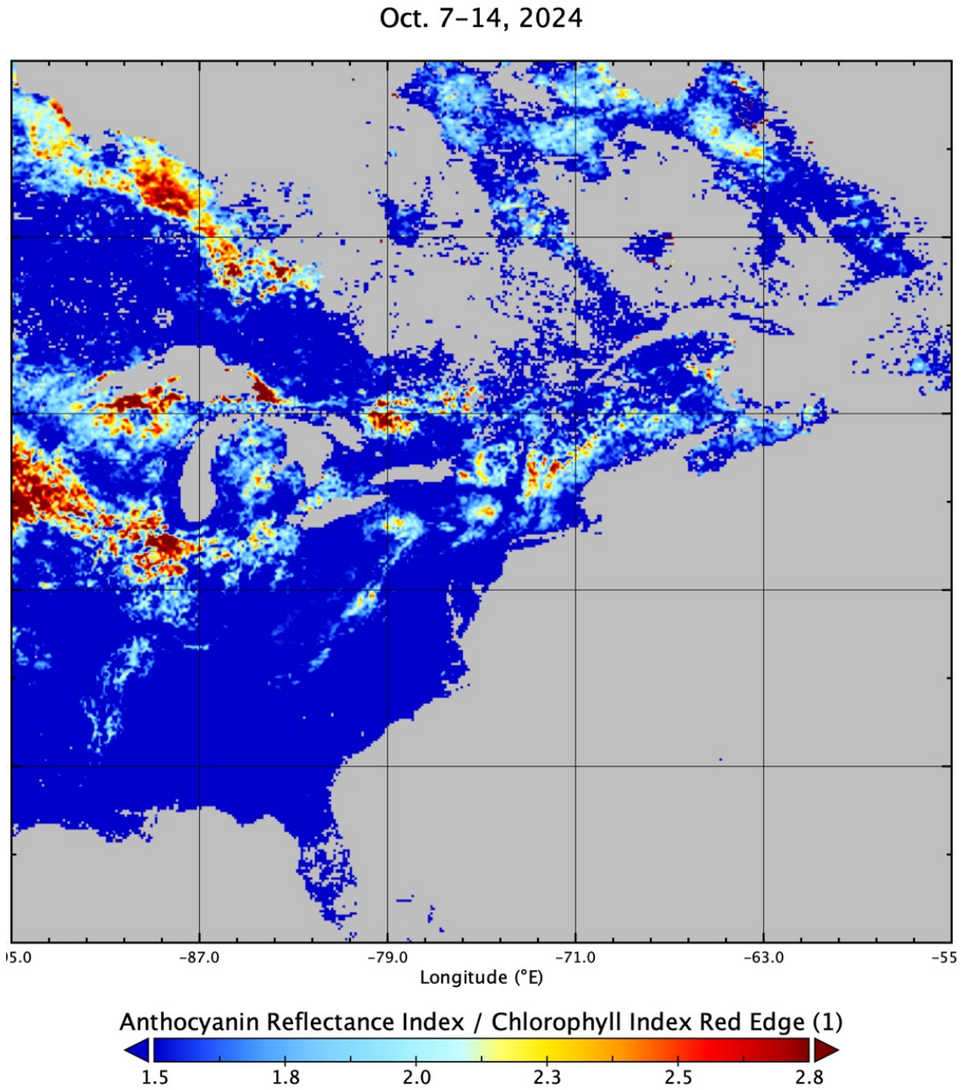
Autumnal Tints from PACE

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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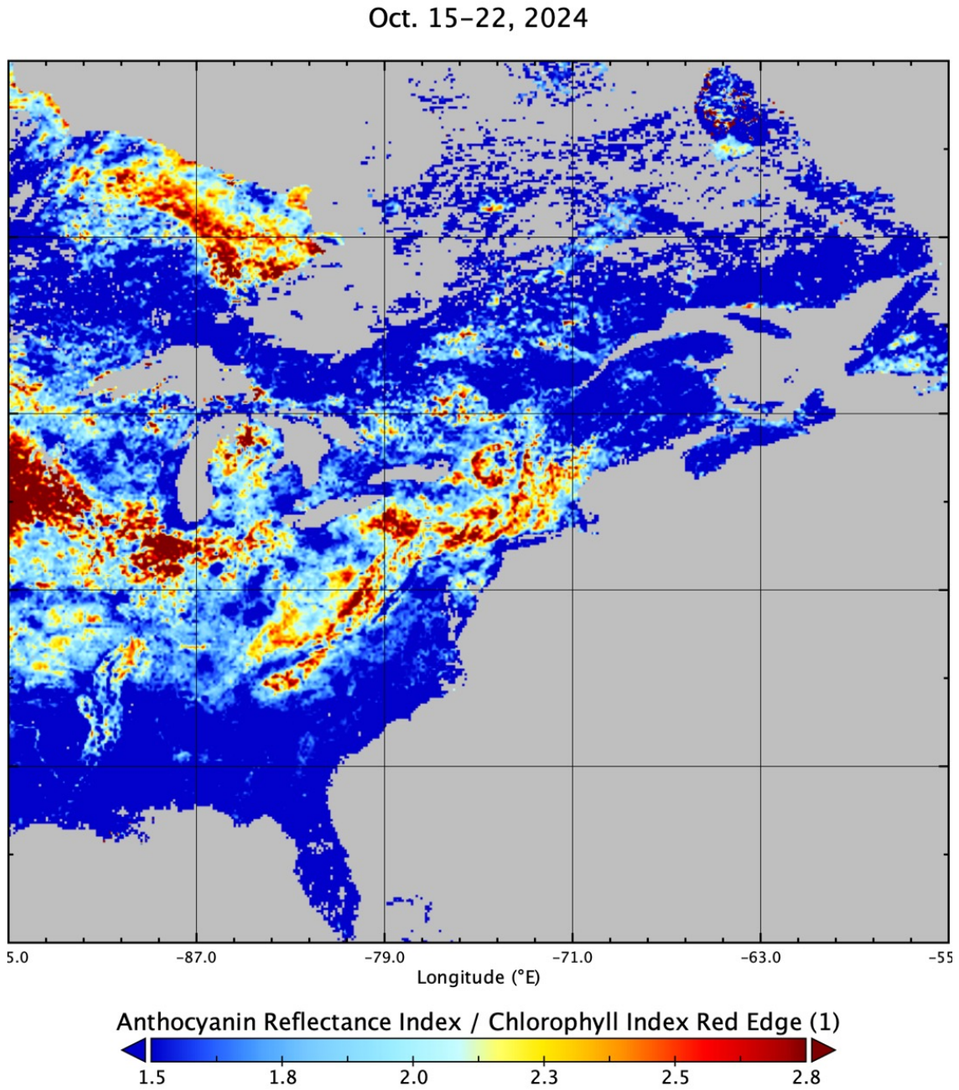
Autumnal Tints from PACE

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



PLUG Jan. 22, 2026

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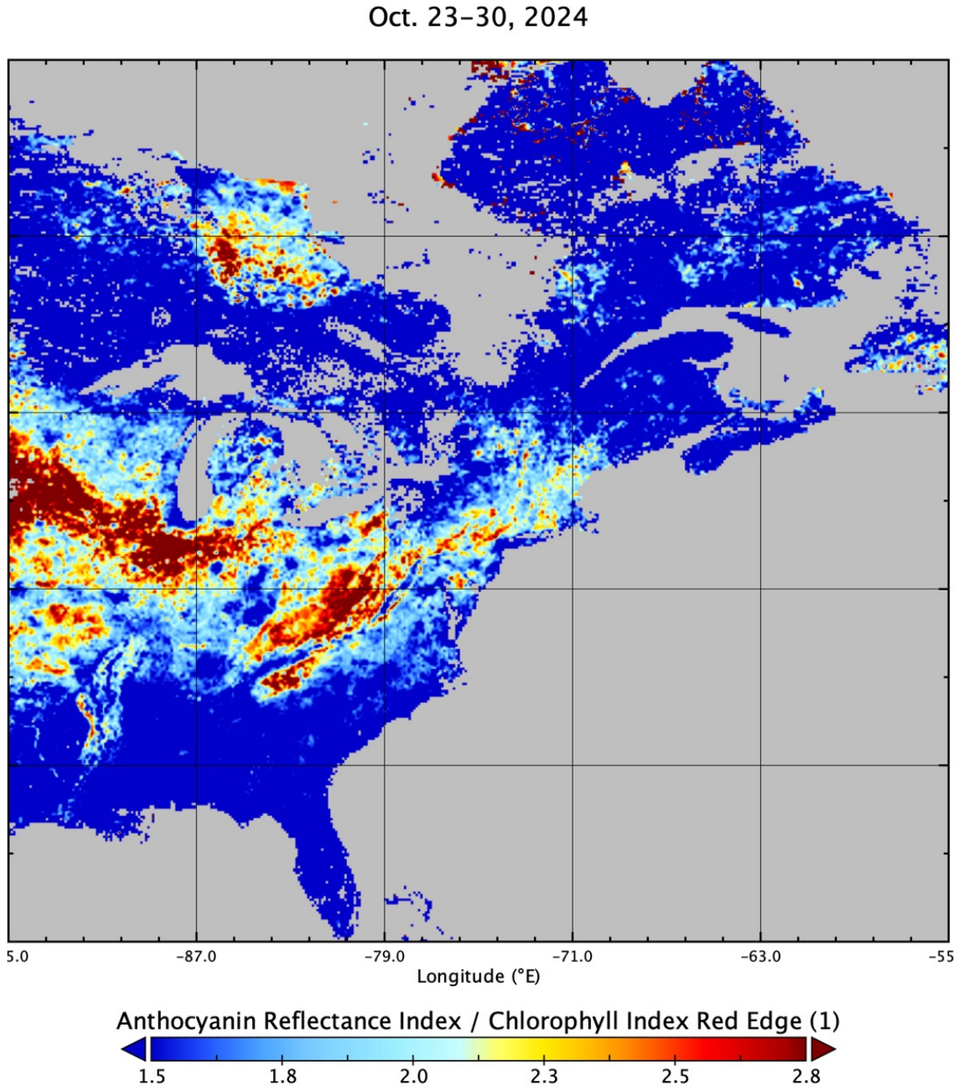
Autumnal Tints from PACE

Now fall color has appeared in the southern Appalachian Mountains



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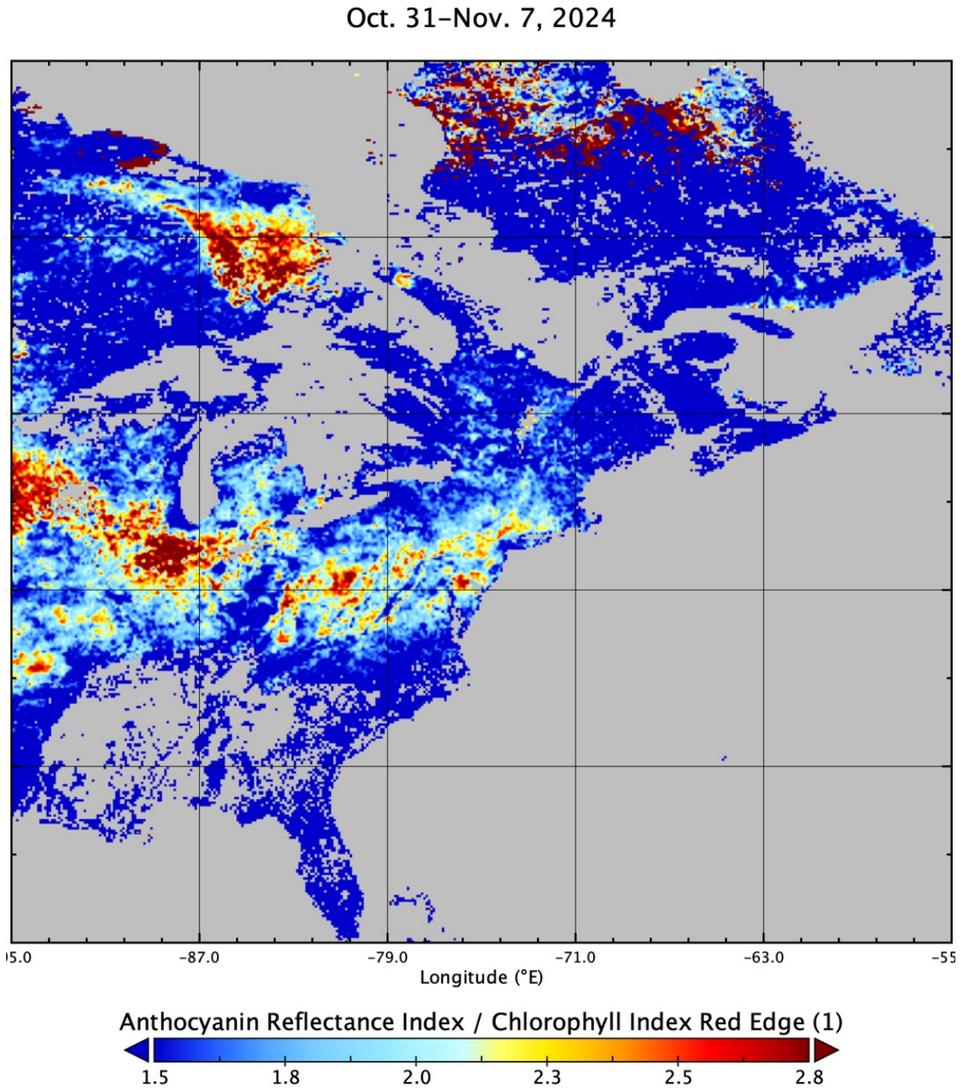

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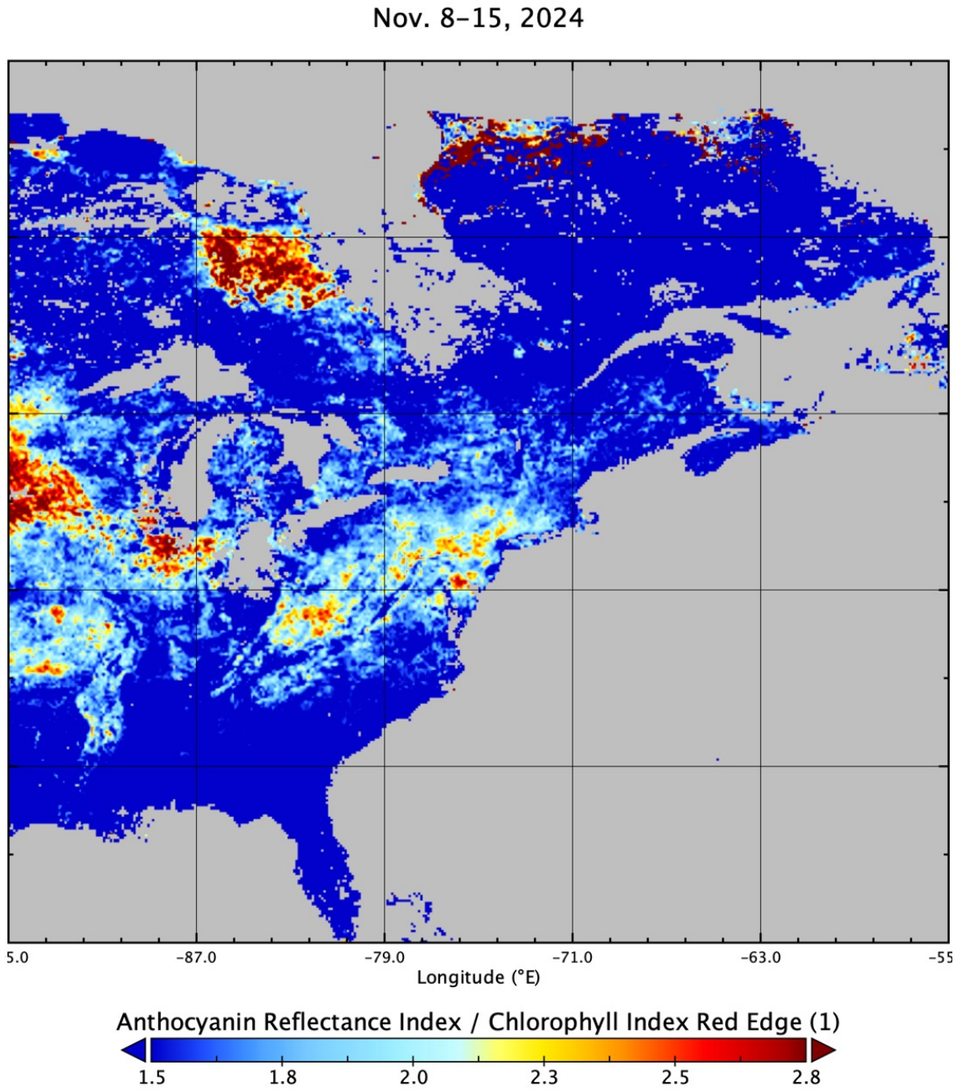

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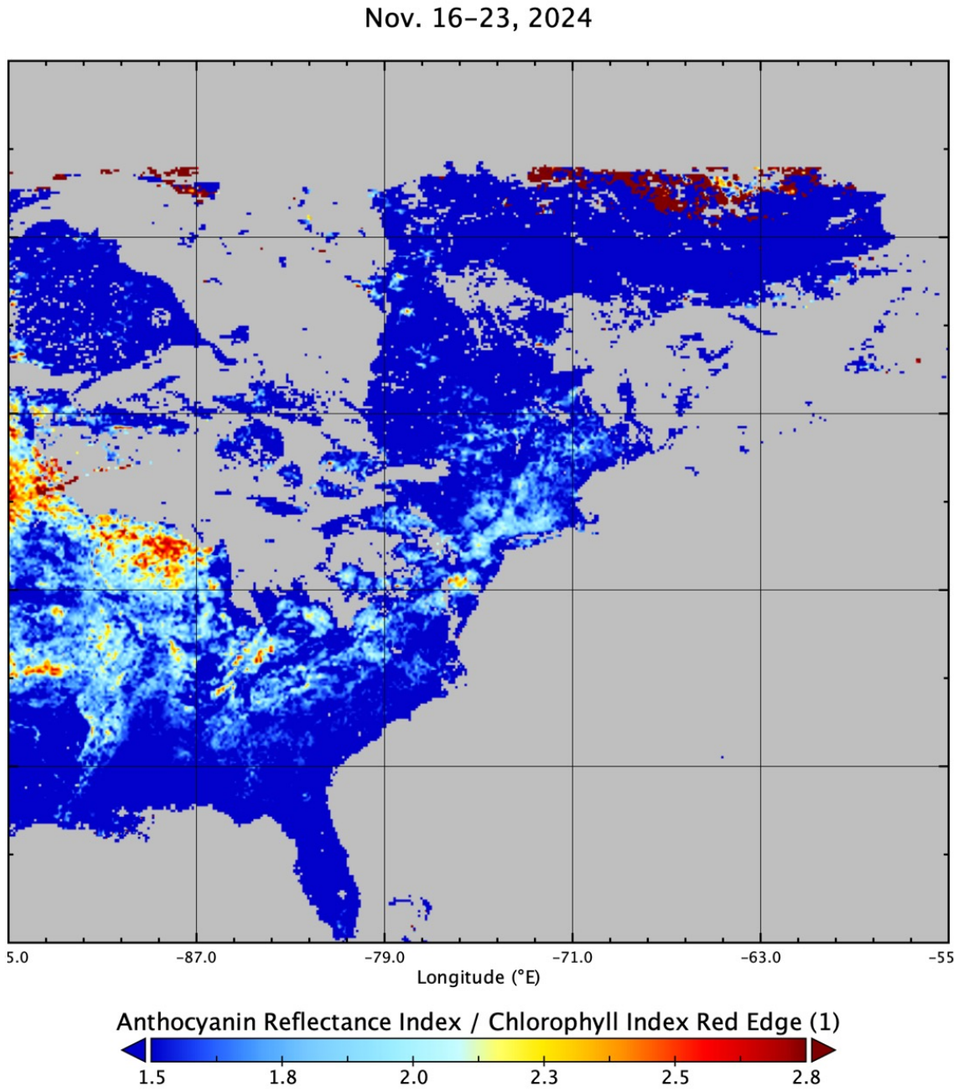
Autumnal Tints from PACE



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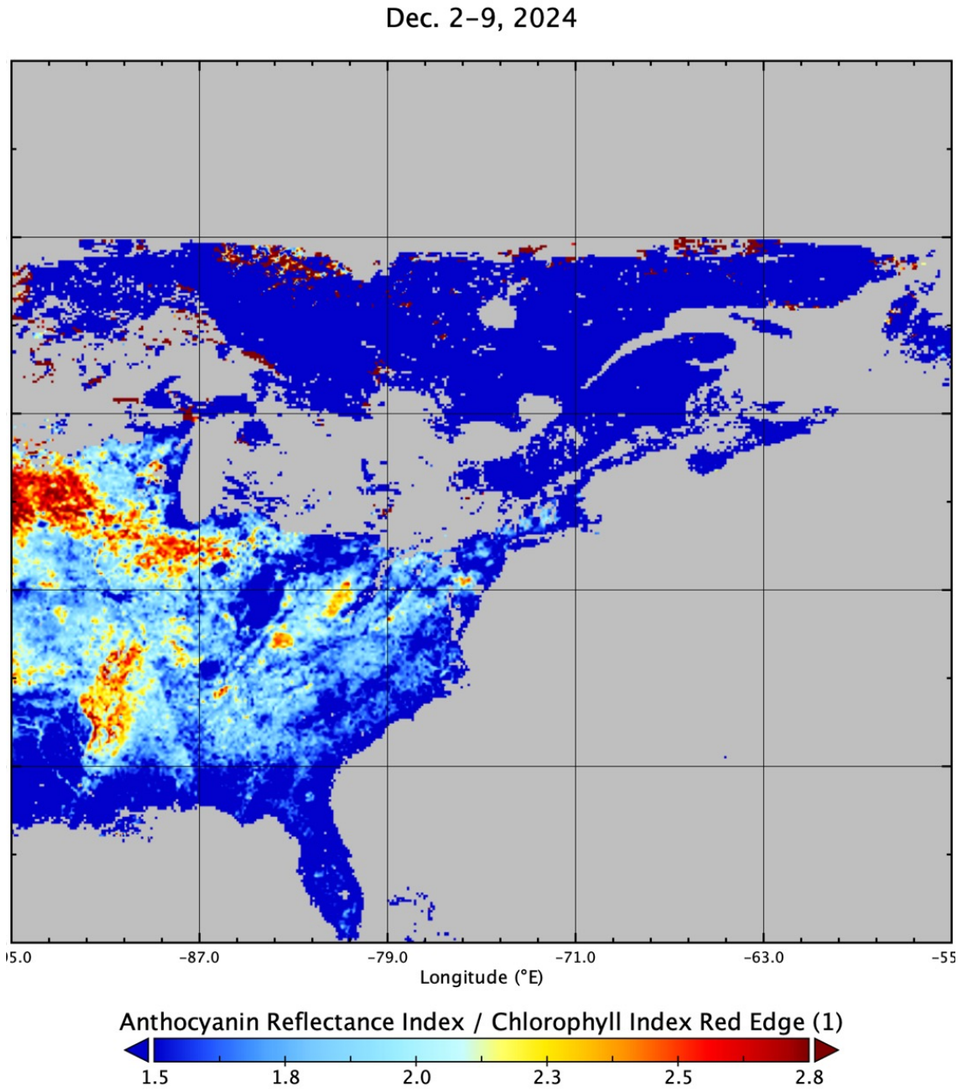
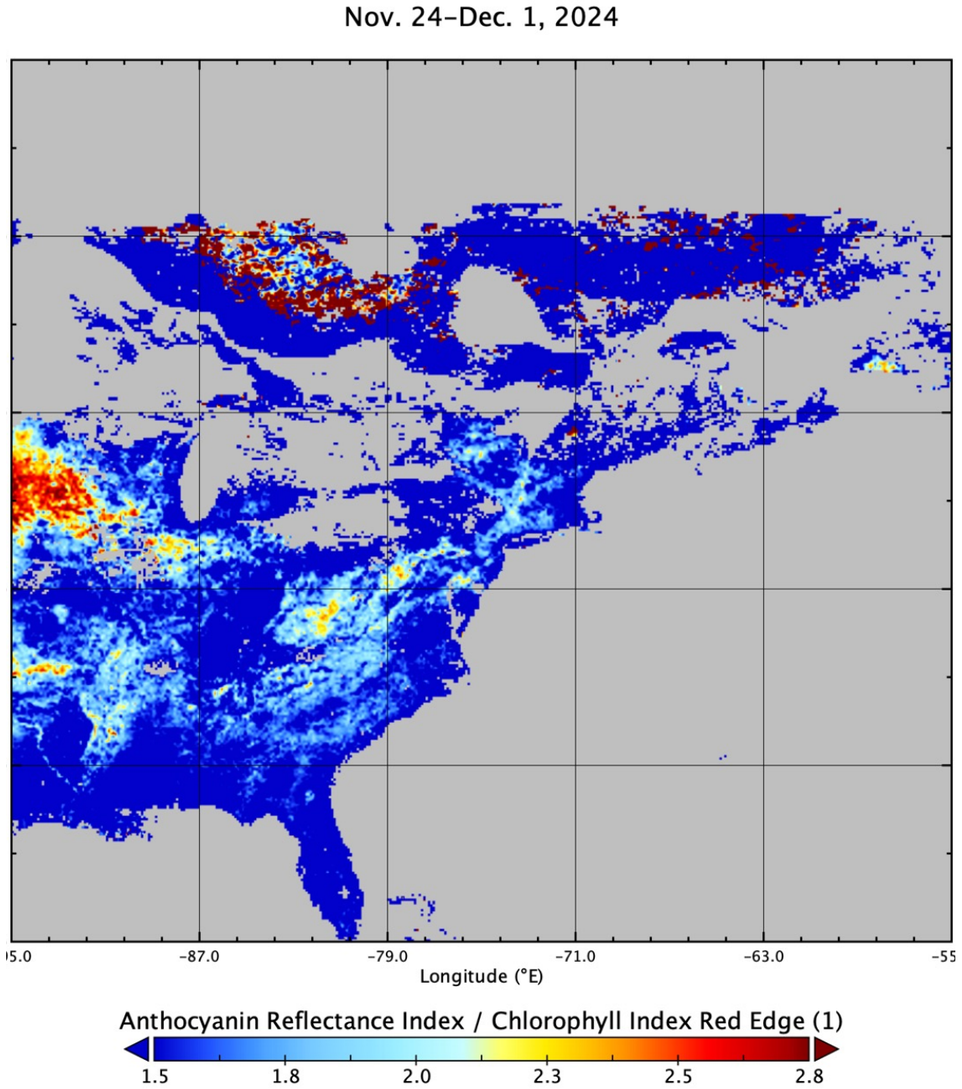
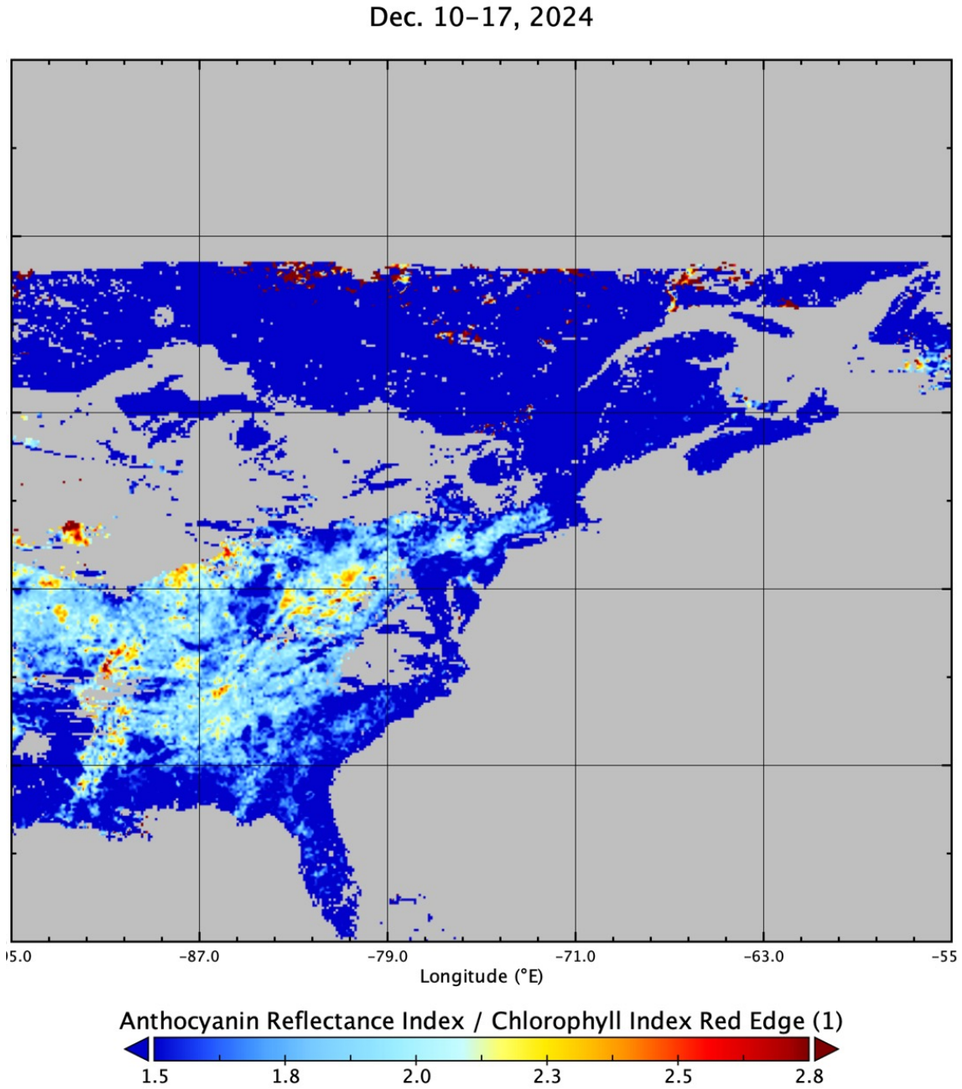


Autumnal Tints from PACE

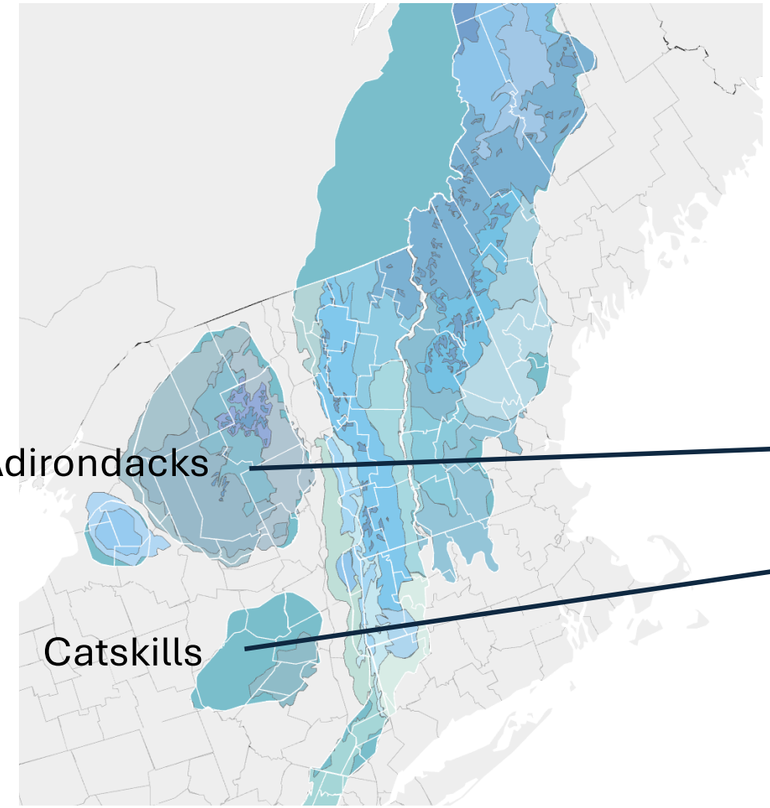


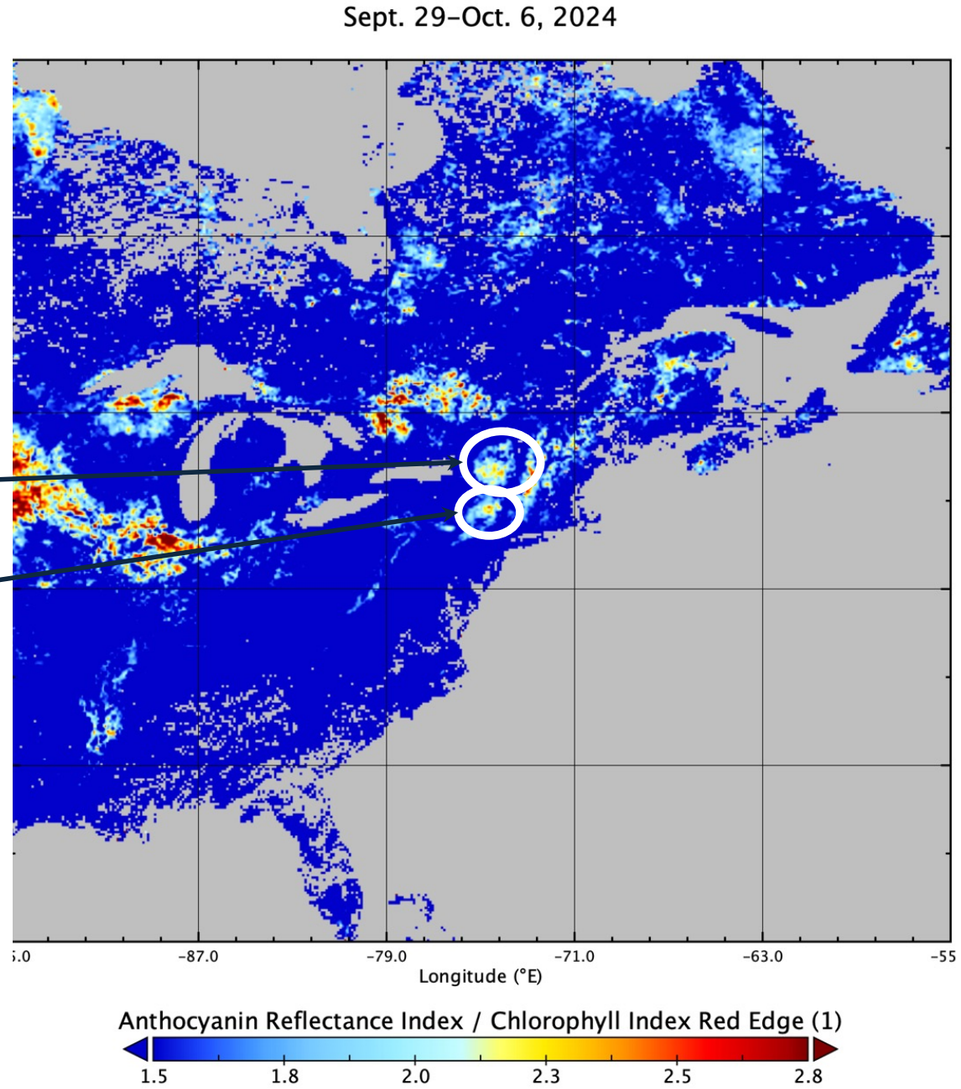
Autumnal Tints from PACE



Autumnal Tints from PACE - Ecoregions

Onset of fall color clearly indicates specific ecoregions





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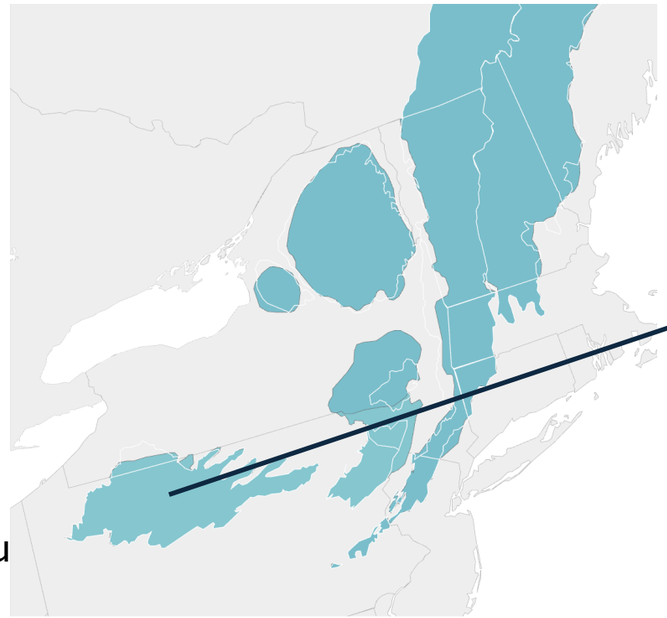
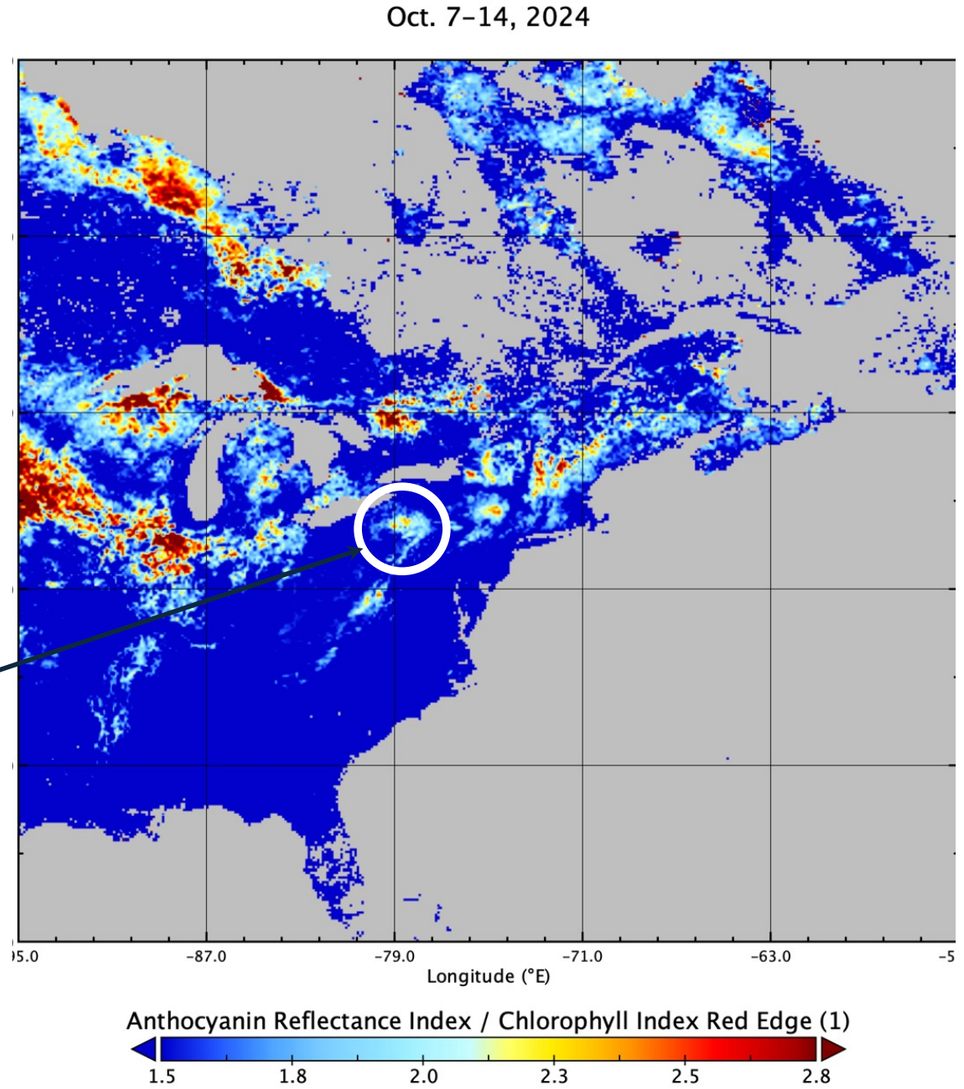
Autumnal Tints from PACE - Ecoregions

Onset of fall color clearly indicates specific ecoregions



Unglaciated High Allegheny Plateau



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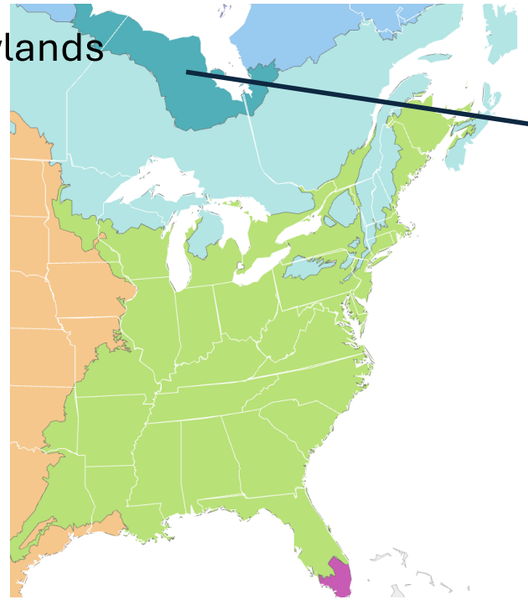
Autumnal Tints from PACE - Ecoregions

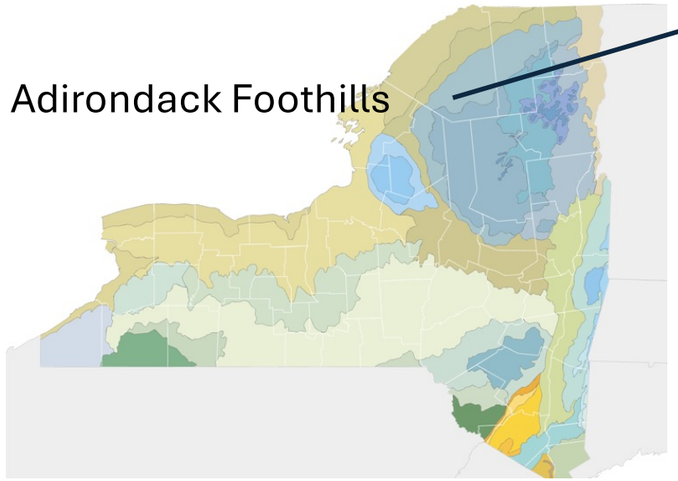
Onset of fall color clearly indicates specific ecoregions

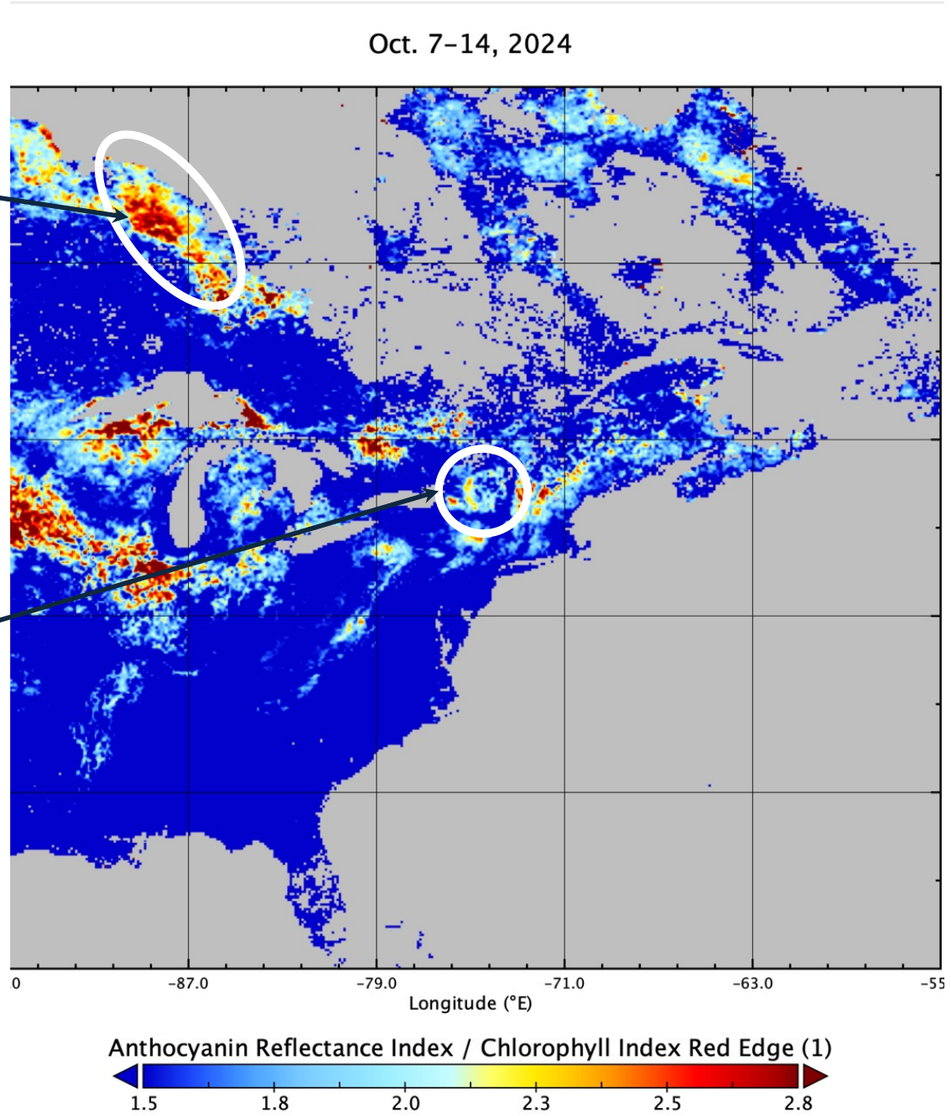
Hudson Bay Lowlands

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



Adirondack Foothills





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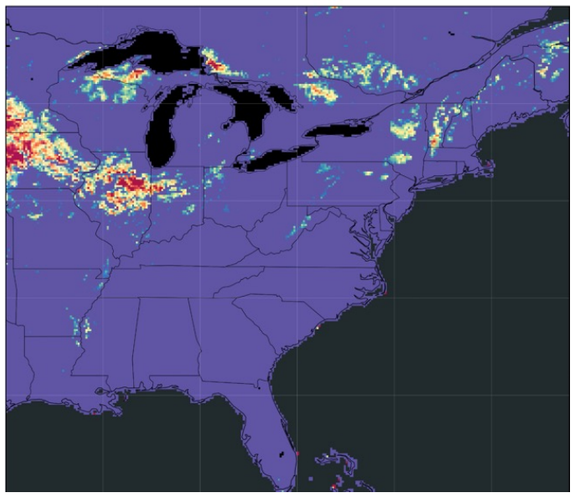
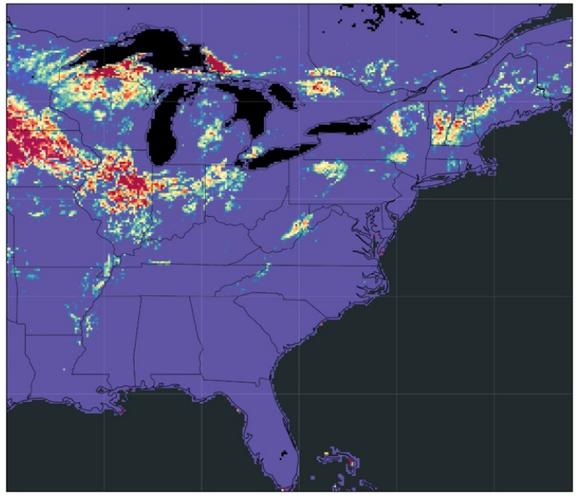
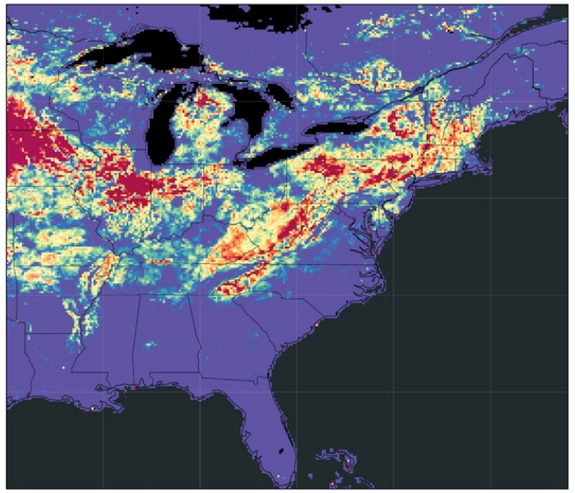
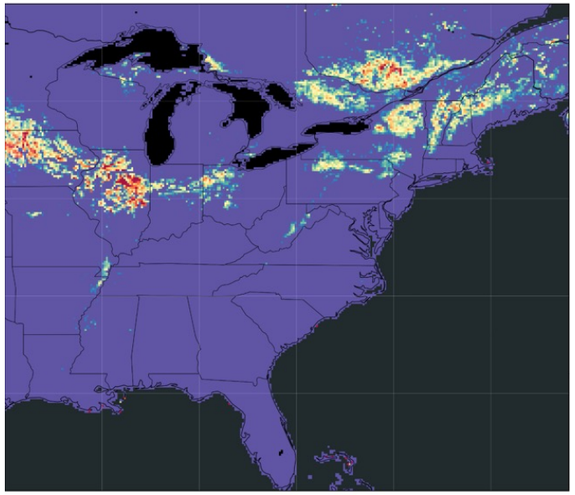
Autumnal Tints from PACE – 2024 and 2025

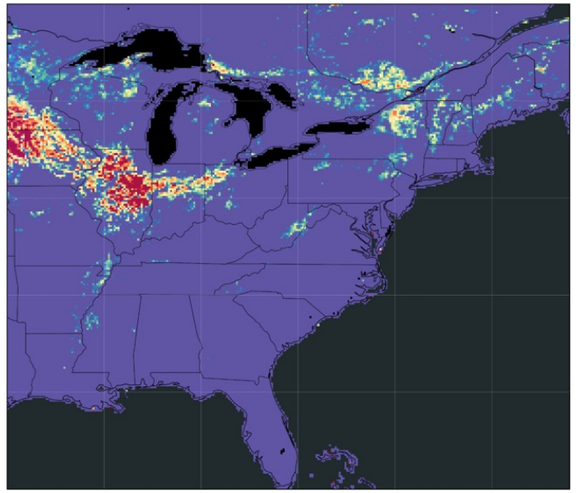
	Sept. 29-Oct. 6	Oct. 7-14	Oct. 15-22
2024	2024 8-day Average mARI/CIRE in Eastern North America 2024-09-29	2024 8-day Average mARI/CIRE in Eastern North America 2024-10-07	2024 8-day Average mARI/CIRE in Eastern North America 2024-10-15
2025	2025 8-day Average mARI/CIRE in Eastern North America 2025-09-29	2025 8-day Average mARI/CIRE in Eastern North America 2025-10-07	2025 8-day Average mARI/CIRE in Eastern North America 2025-10-15

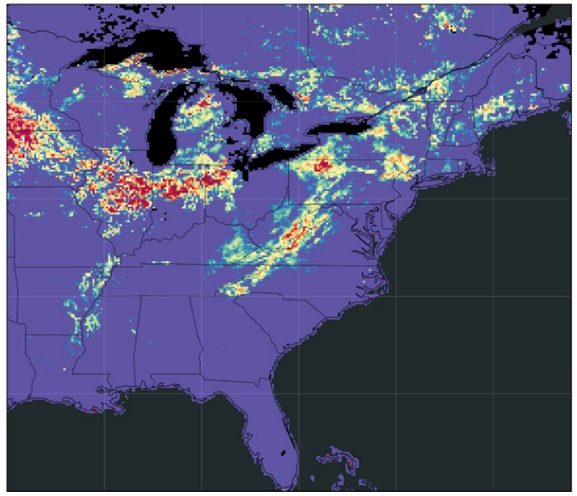












Earlier start of fall colors in north in 2025

Earlier fall colors in Appalachian Mountains in 2024

PLUG Jan. 22, 2026

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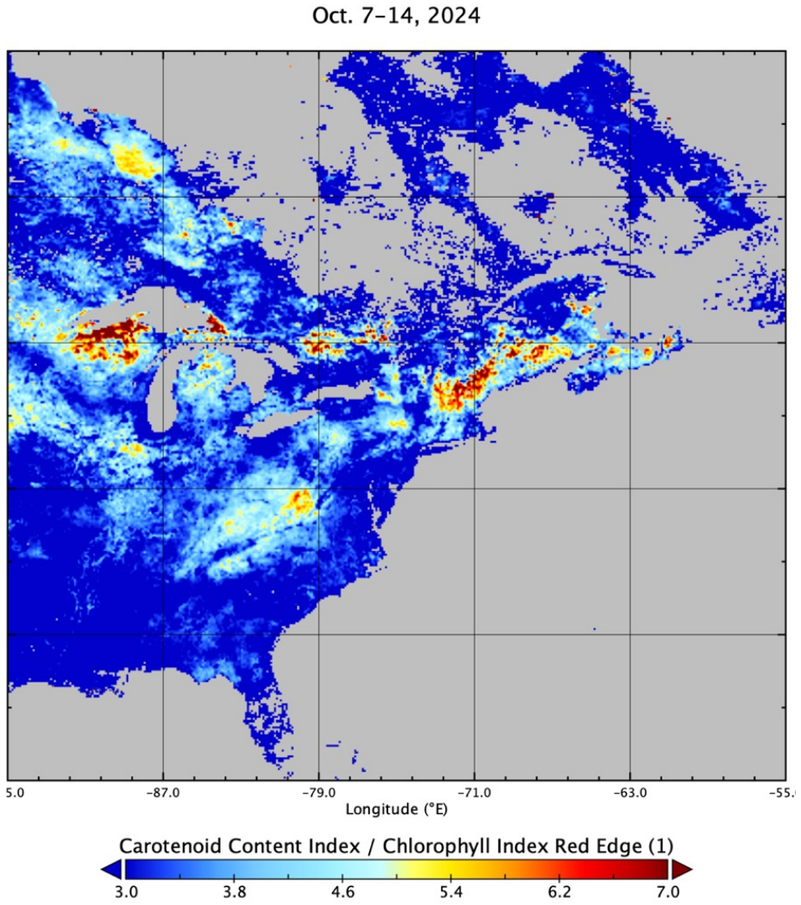
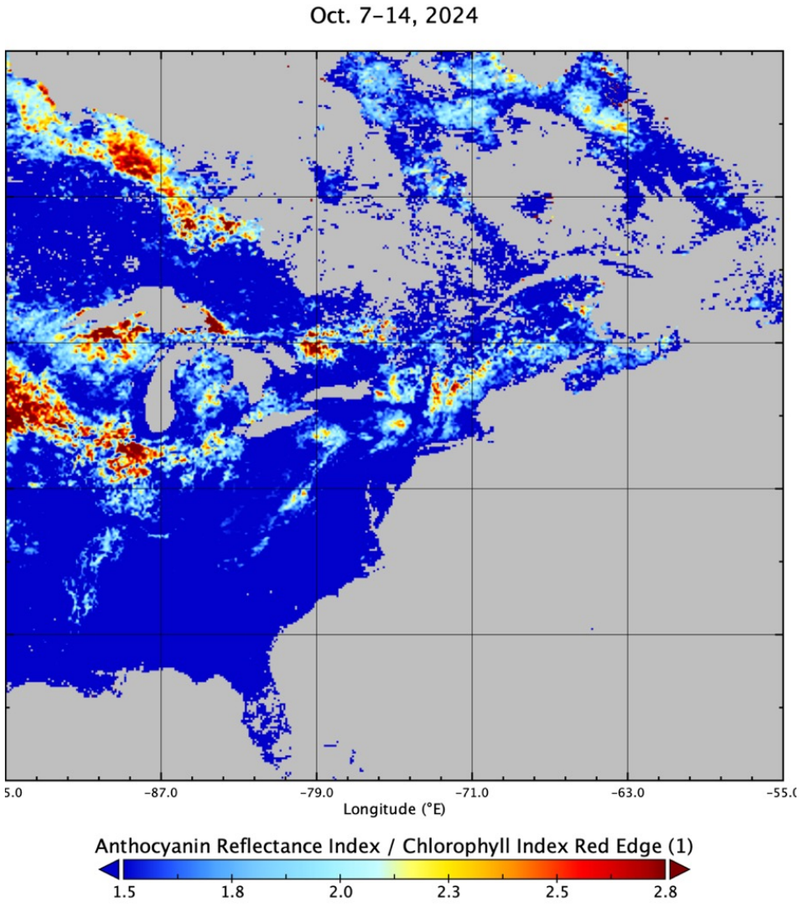
Autumnal Tints from PACE – Carotenoids (yellow) and Anthocyanins (red)

Carotenoid Index /Chlorophyll Index



Anthocyanin Index /Chlorophyll Index



Different spatial patterns emerge when viewing different pigments

For Car/Cire, Corn belt is less prominent, color change in southern Appalachians is stronger

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

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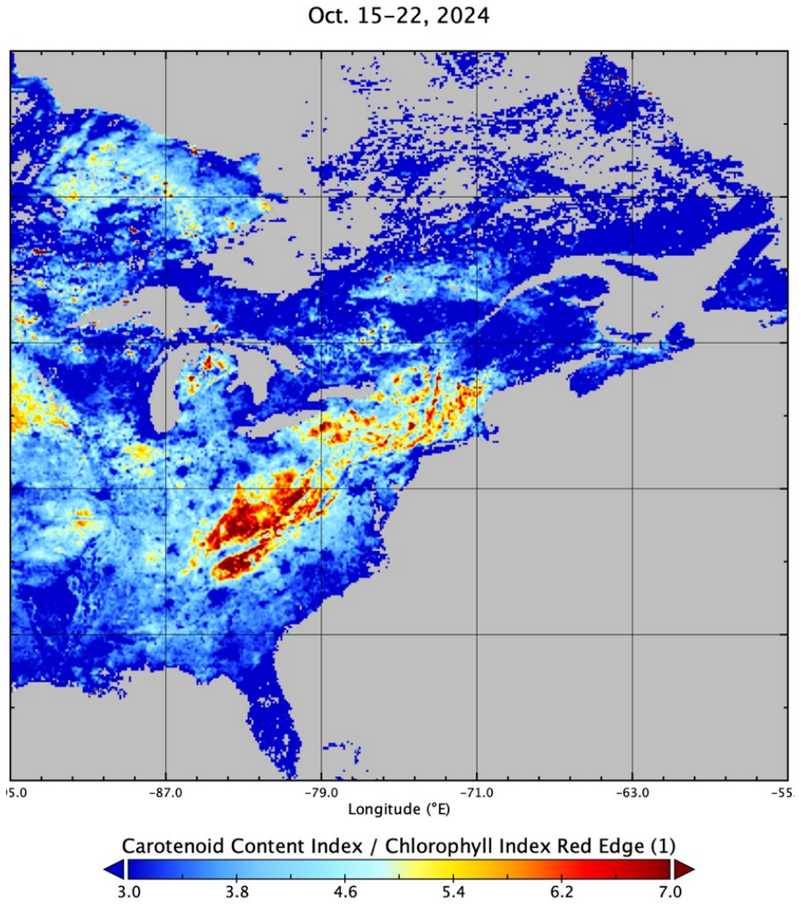
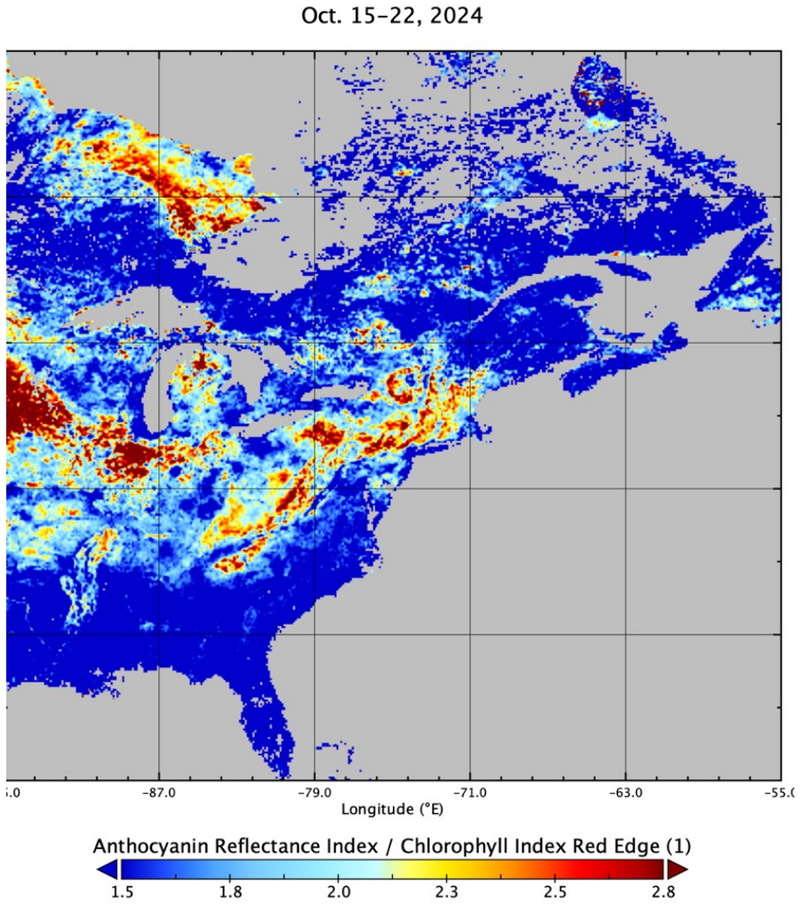


Anthocyanin Index /Chlorophyll Index



Different spatial patterns emerge when viewing different pigments

For Car/Cire, Corn belt and Hudson Bay lowlands are less prominent, color change in southern Appalachians is stronger

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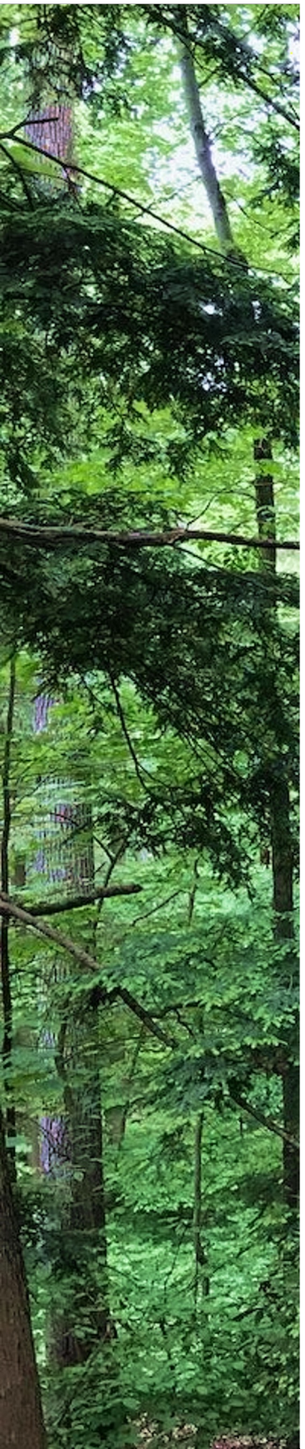
Conclusions

Autumn senescence is an important seasonal event in the deciduous forests of eastern North America

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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