PhenoCam: Monitoring vegetation phenology with networked digital cameras

Applications to evaluation of remote sensing products

Andrew D. Richardson
Harvard University

Collaborators:
Mark Friedl and Koen Hufkens (Boston University),
Bobby Braswell (Atmospheric & Environmental Research),
Mirco Migliavacca (University of Milan),
Thomas Milliman (University of New Hampshire),
and FLUXNET Data Providers

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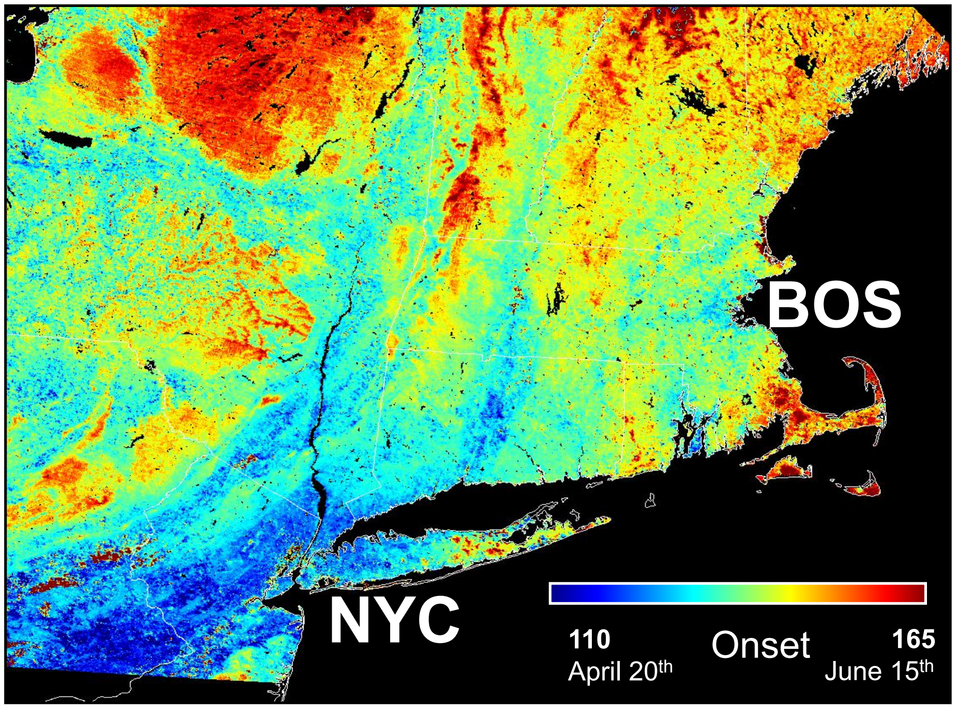
Phenology:
Easily observed from space!

Spring onset estimated from MODIS varies by 2 months across New England



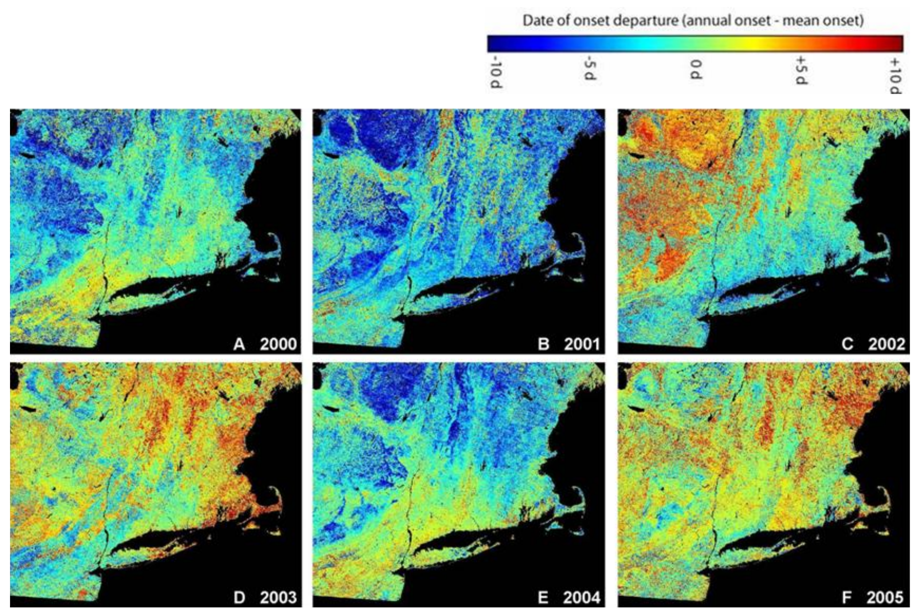
Source: Fisher and Mustard RSE 2007.

Observed gradients:

- Latitudinal
- Longitudinal
- Elevational
- Continental/maritime
- Species composition

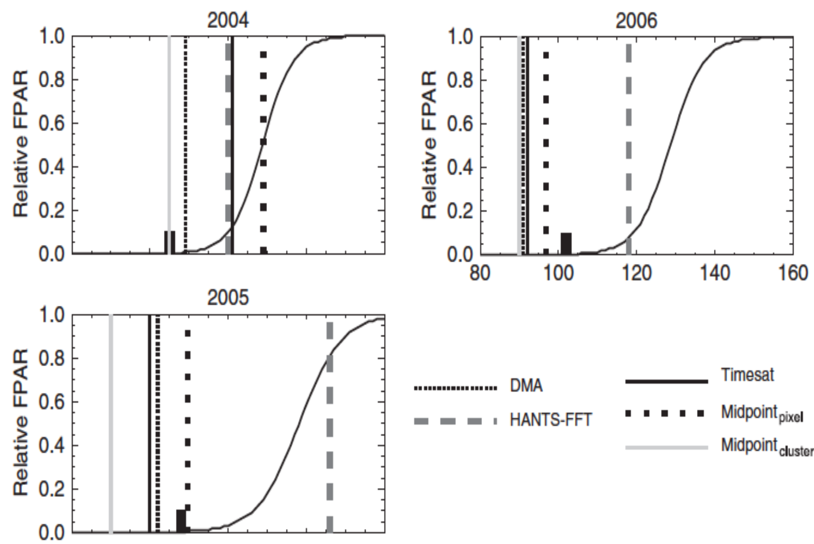
Substantial interannual variability:

- ± 3 weeks from year-to-year
- varying spatial homogeneity
- differing amounts of variability



… or perhaps not?

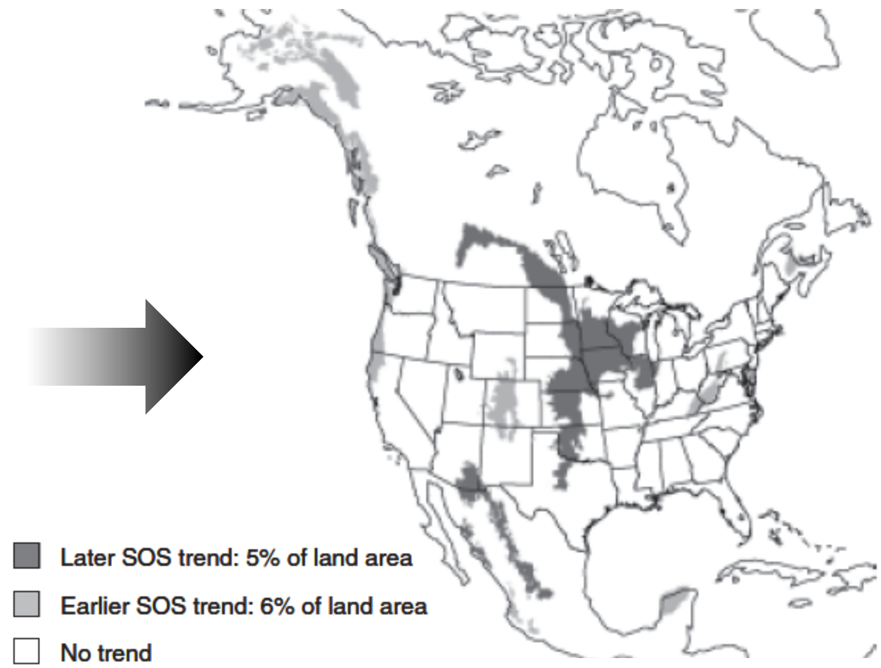
White et al. 2009. Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982–2006. *Global Change Biology* 15: 2335-2359.



Using a consistent data set, different algorithms predict different onset dates, but these do not correspond to ground-based measurements of fAPAR, and but patterns of bias are variable in time.

Trends in spring onset

- Spatially variable
- Not resolved for most of continent
- Differ among algorithms
- Both earlier and later spring observed



The Question:

Can we use satellite-based observations to accurately detect and quantify variability in phenology?

- Spatial patterns (at what scale: pixels to regions?)
- Temporal patterns (over what time period: seasons to decades?)

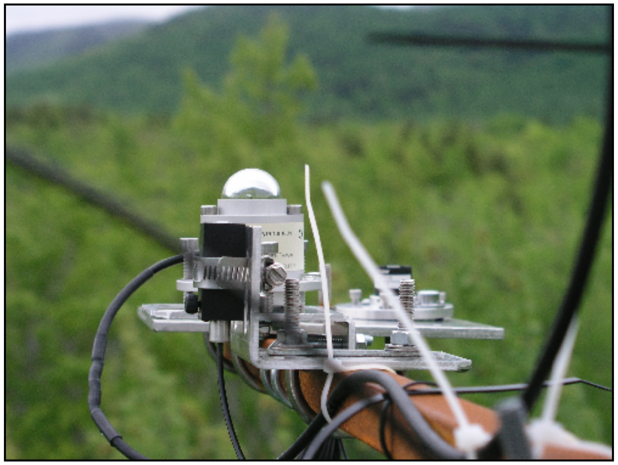
Two Outstanding Challenges:

What does satellite-based "onset" or "senescence" correspond to, in terms of canopy structure or physiological activity?

What are the uncertainties?

Monitoring phenology of ecosystems:

Ideal application of "near-surface" remote sensing



Quantify canopy development and senescence with instrument-based optical measurements

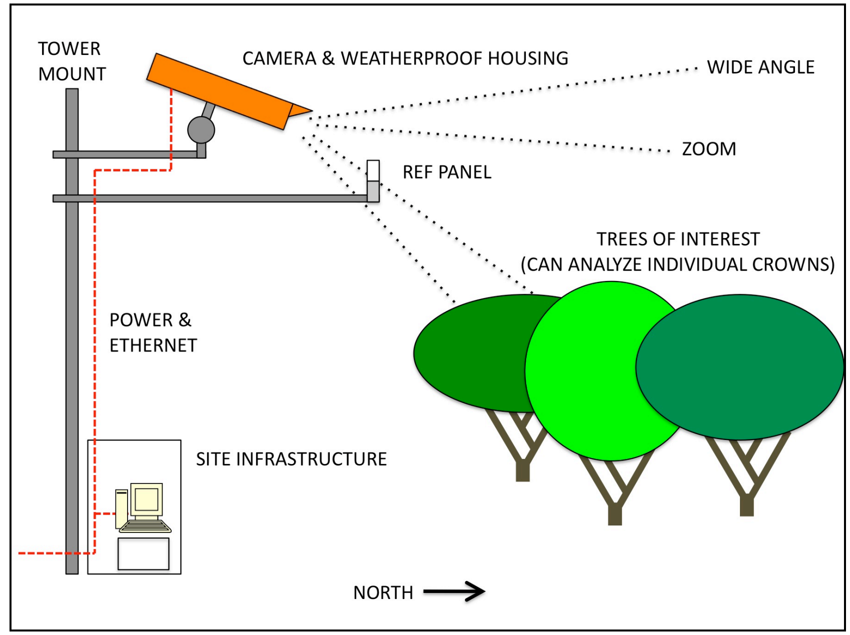
- Radiometric sensors ($f_{APAR,}$ Broadband NDVI)
- Webcam imagery (changes in RGB signal)

Overcome some limitations of both observer-based and satellite RS phenology

Provides phenology data continuously in time, at scale complementary to flux measurements and satellite pixels

	Pros	Cons
Field observations	• Characterize phenophases • Observe individual plants • Observe species of interest	• Spatial coverage • Temporal resolution • Time consuming • Observer bias, subjective
Satellite RS	• Spatial integration • Global coverage	• Spatial resolution • Temporal resolution • Cloud cover • Atmospheric corrections • Uncertain interpretation
Near-surface RS	• Spatial integration • Continuous in time • Relatively inexpensive	• Infrastructure required • Instruments may fail • Uncertain interpretation

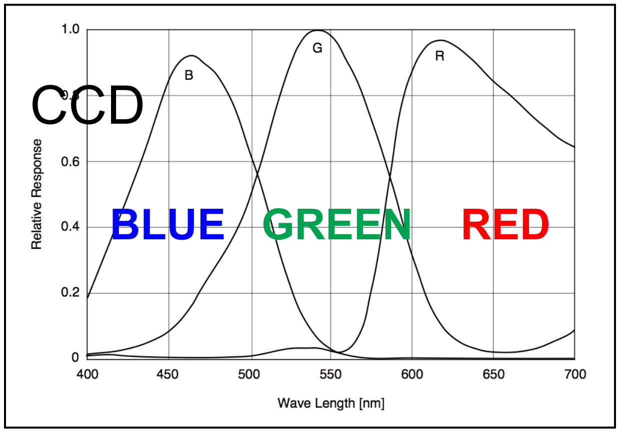
Webcam monitoring of phenology



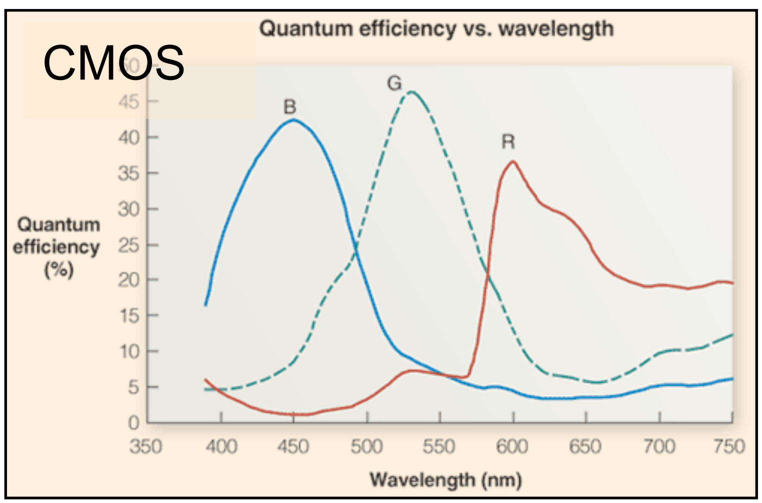
- Commercially available webcam mounted on tower
  - Faces north
  - 15° below horizontal
  - Spatial integration (but individual crowns could be analyzed)
  - Images recorded between noon and 2 pm daily, uploaded by ftp to web page
- Provides a permanent visual record
- Image analysis (RGB channel extraction) to quantify phenological changes
- Direct link between what is happening on the ground and what is seen by satellites
- Not a calibrated instrument—but neither are field observers!

Camera technical specifications

Spectral response of sensors



Sony Corp. (http://products.sel.sony.com/semi/PDF/ICX098BQ.pdf)

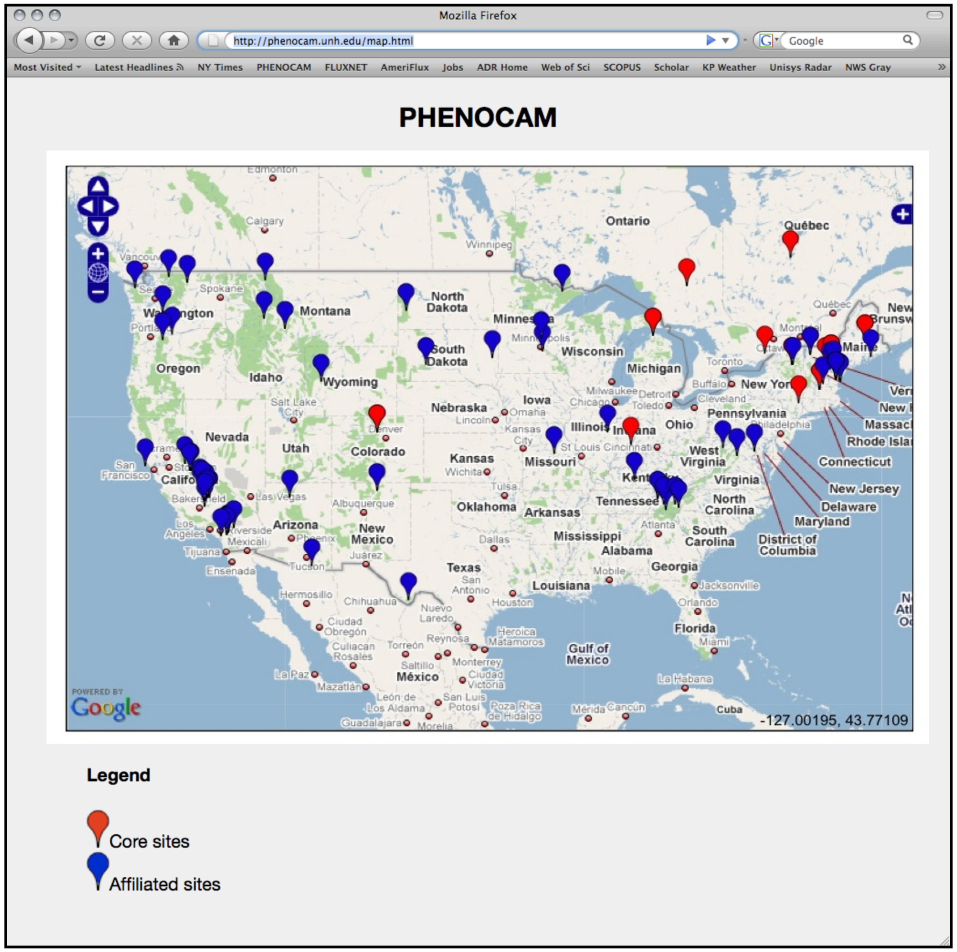


http://images.pennnet.com/articles/vsd/thm/th_0707vsd_prfocus01.gif

- Initial work: **Axis 211** model camera, 640 x 480 pixel resolution (0.3 M pixel), Sony progressive scan RGB silicon CCD, IR filter blocks > 700 nm
- Now: StarDot **NetCam SC**, 1280 x 960 pixel resolution (1.3 MP), Micron ¼" CMOS sensor, IR filter triggered on schedule
- Fixed white balance (outdoor), auto exposure, variable iris
- Images stored as minimally compressed jpeg files
- New project: ***CamCom* Experiment** (Harvard Forest, summer 2010)

Continental-scale PhenoCam coverage

Some data records 8+ years in length



Images mirrored to server 50+ sites covering a wide range of ecosystem types.
Potential collaboration with AMOS (Archive of Many Outdoor Scenes): ~20,000 cameras!

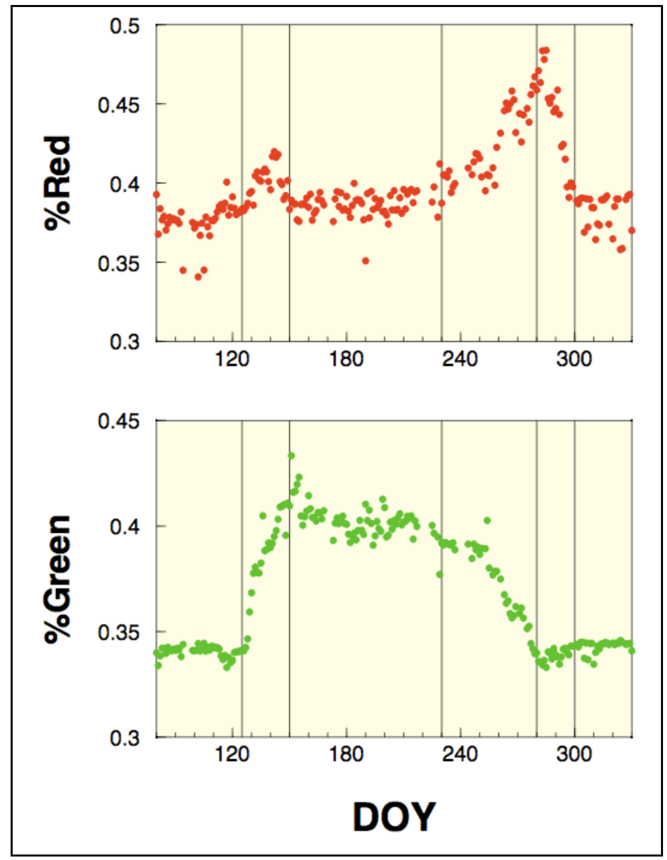
Initial results:

Seasonal patterns in a deciduous forest

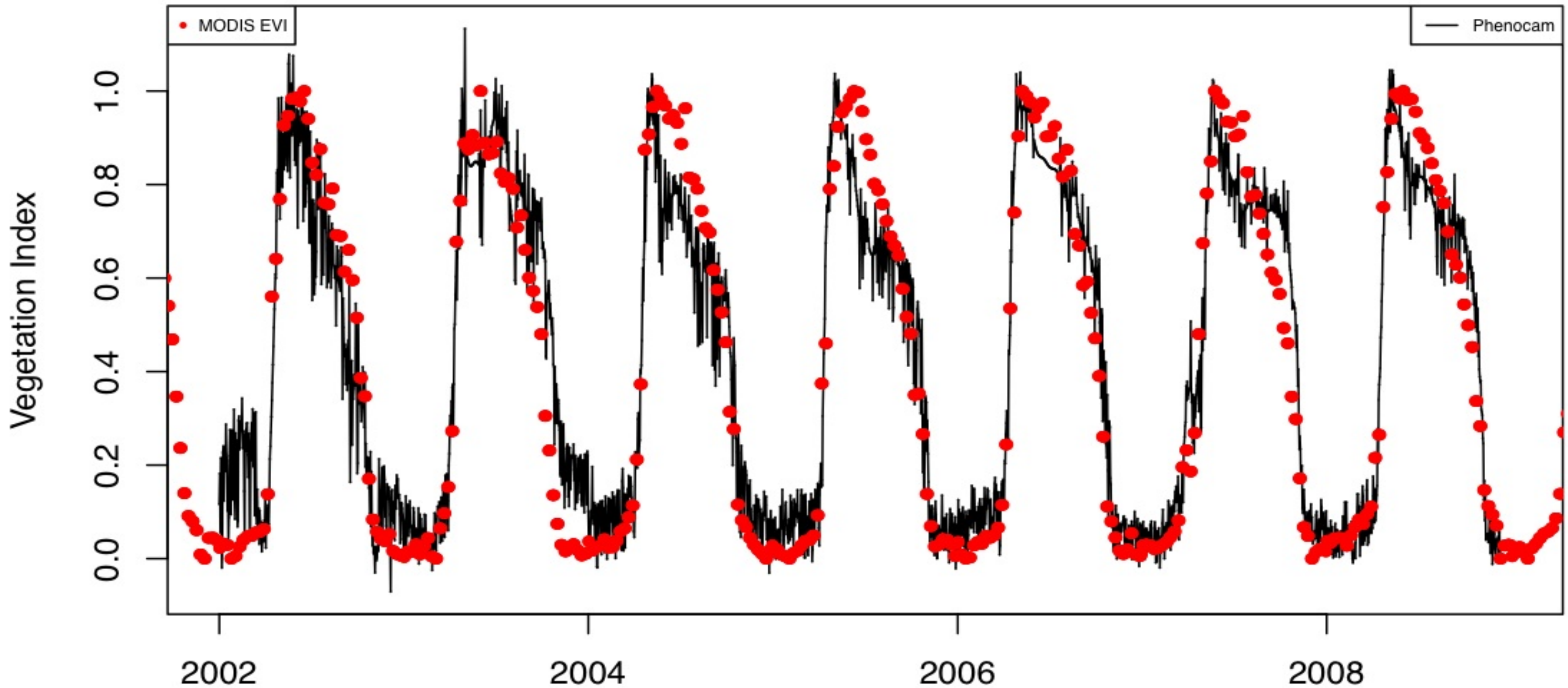
Conducted image analysis on a pre-defined region of interest (image foreground).

Relative brightness of red (%Red) and green (%Green) channels show strong seasonal patterns:

- Timing and speed of spring green-up and autumn green-down
- Timing and peak intensity of autumn coloration



Camera greenness vs. MODIS EVI



Mammoth Cave, Kentucky (2002-2009)

Long-term records, potential to characterize anomalies

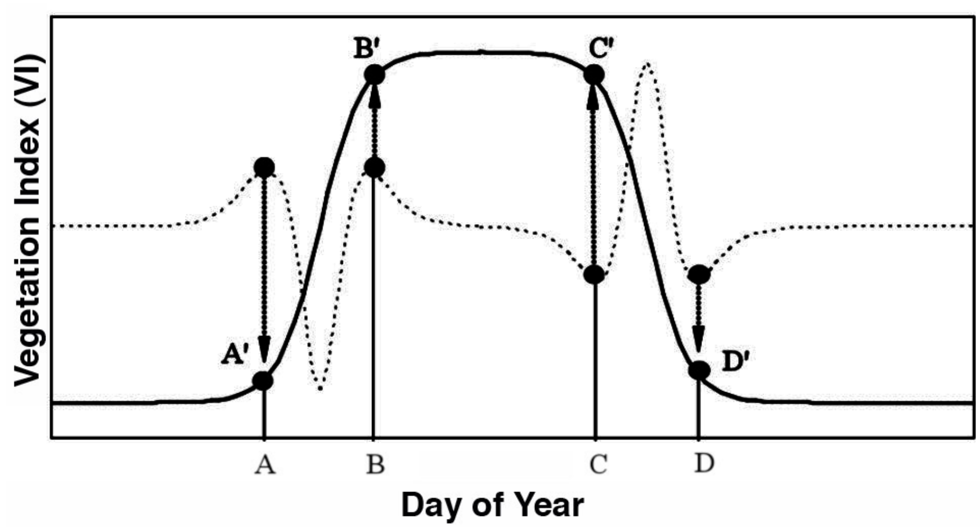
Reasonable synchrony in time series

Good signal-to-noise ratio in both

MOD12Q2 Transition date retrieval

- Dual logistic functions $g(x)$ fit to annual EVI time series
- Identify 3rd derivative max/minima (correspond to to 10% & 90% of EVI range) as threshold dates
- Other approaches possible
  - Half-maximum (e.g. Fisher et al. 2007)
  - Maximum curvature
  - Specific VI thresholds…
- May need to consider alternative functional forms (Gompertz etc.)

$$g(x) = a + \frac{b}{\left[1 + \exp(c - dx)\right]}$$



Spring thresholds:

A–Onset of greenness

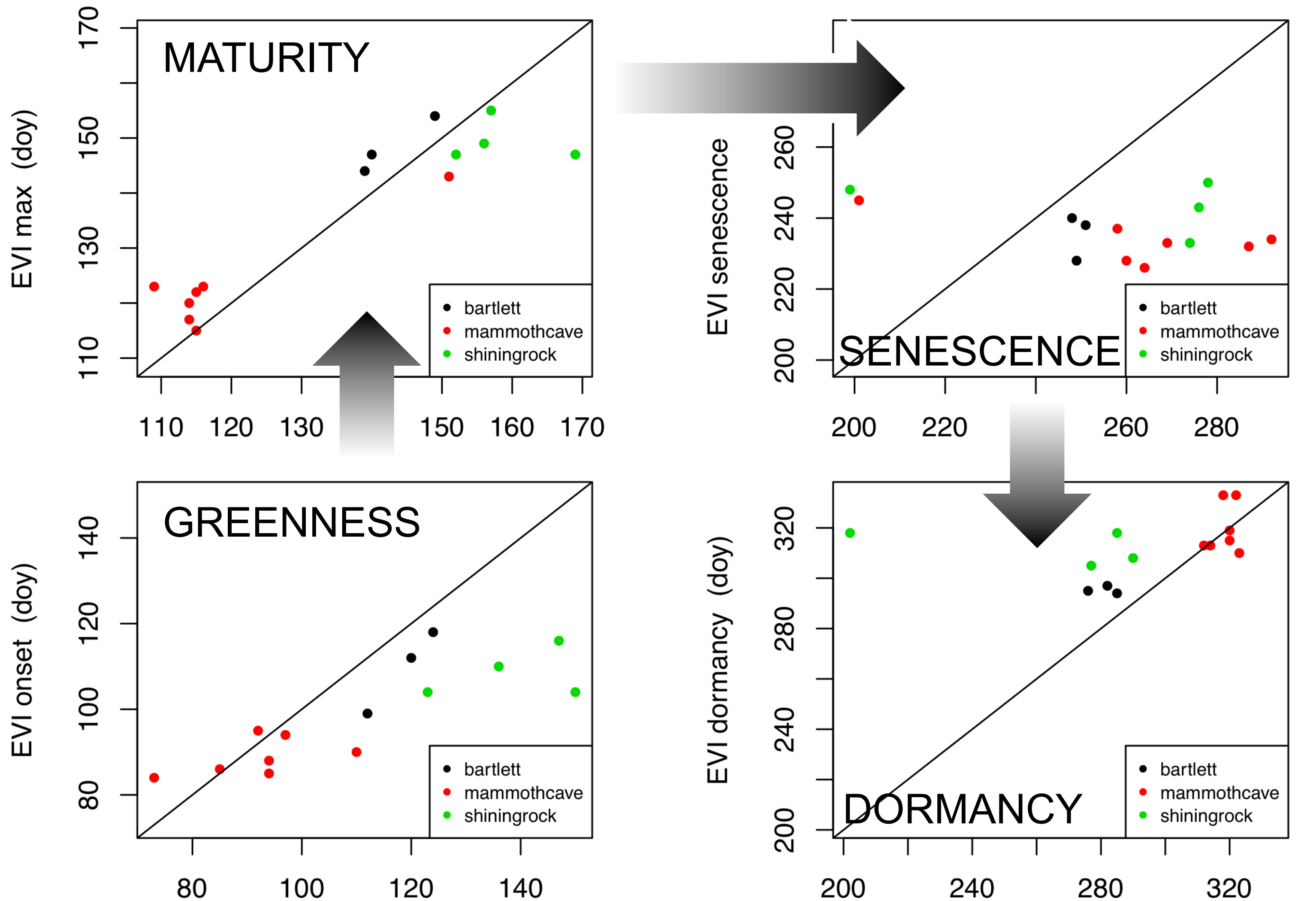
B–Onset of maturity

Autumn thresholds:

C–Onset of senescence

D–Onset of dormancy

Comparison of retrieved thresholds

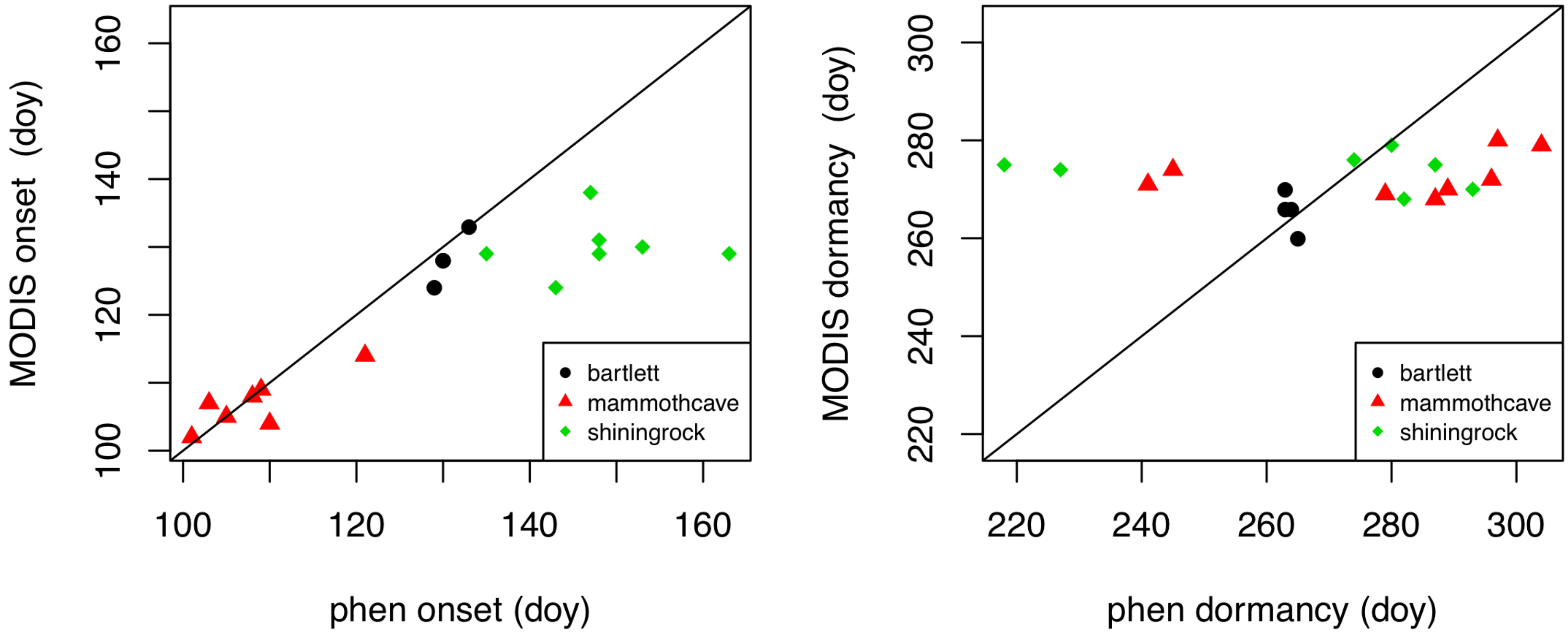


Agreement better for spring, compared to autumn, transitions

Better retrieval of spatial patterns than interannual variability

Results promising (just 3 sites used here) but indicate substantial uncertainties

Sigmoid half-maximum dates

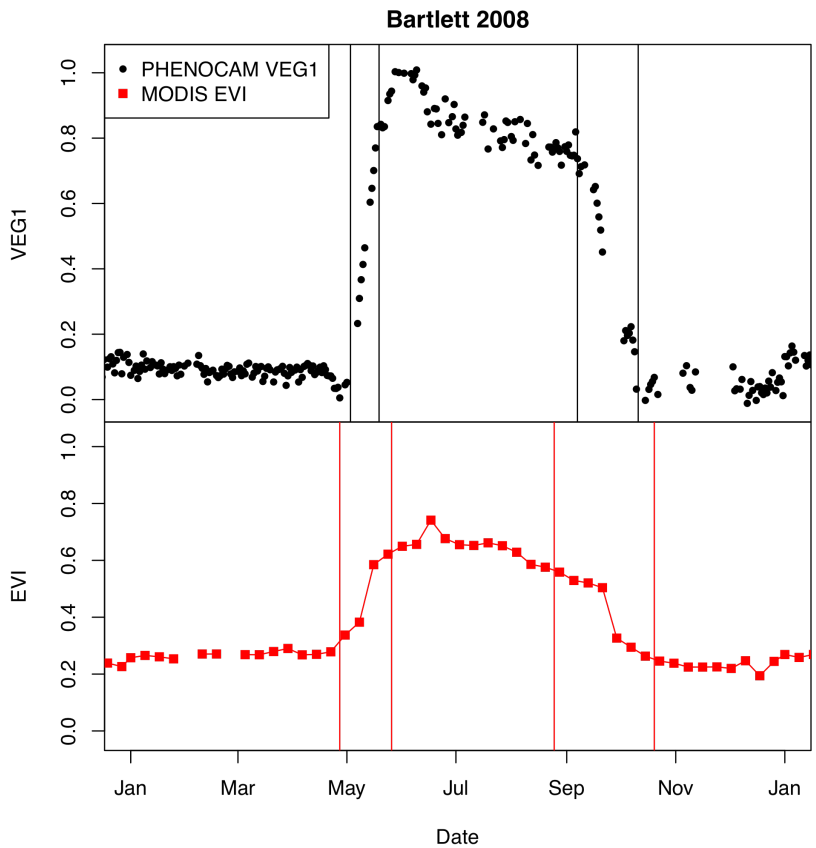


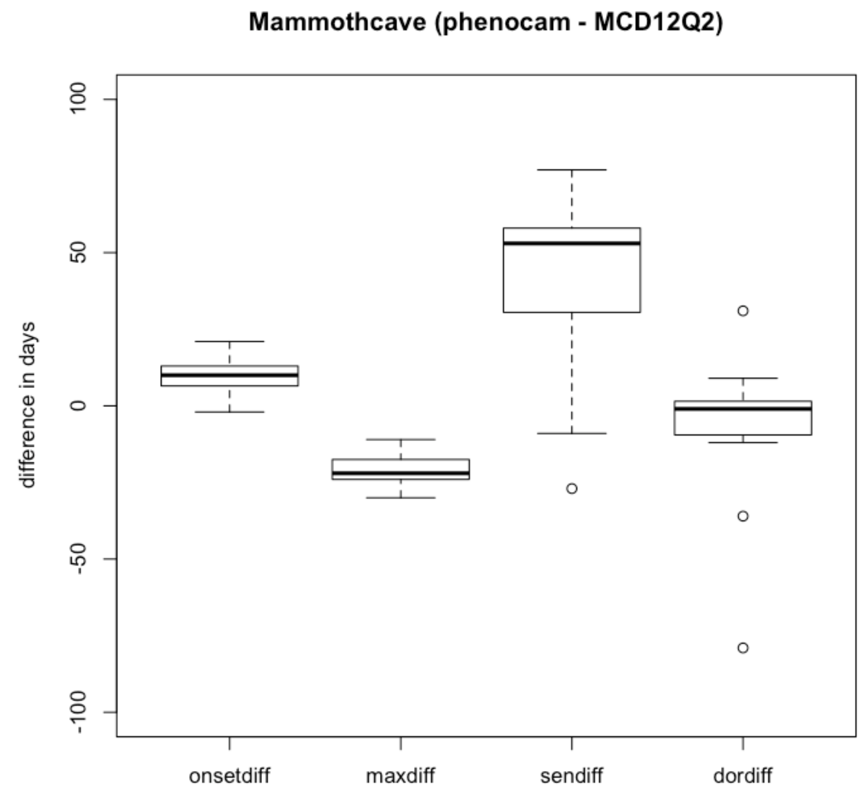
Good performance in spring for 2 of 3 sites (more noise in Shining Rock camera imagery)

Still very poor performance in autumn — cameras and satellites tracking different canopy properties

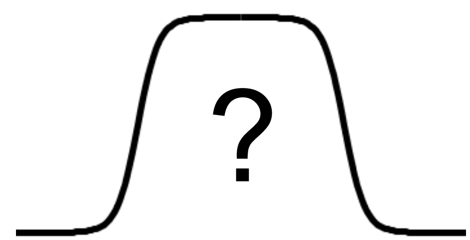
Why aren't we doing better?

Summary of overall patterns



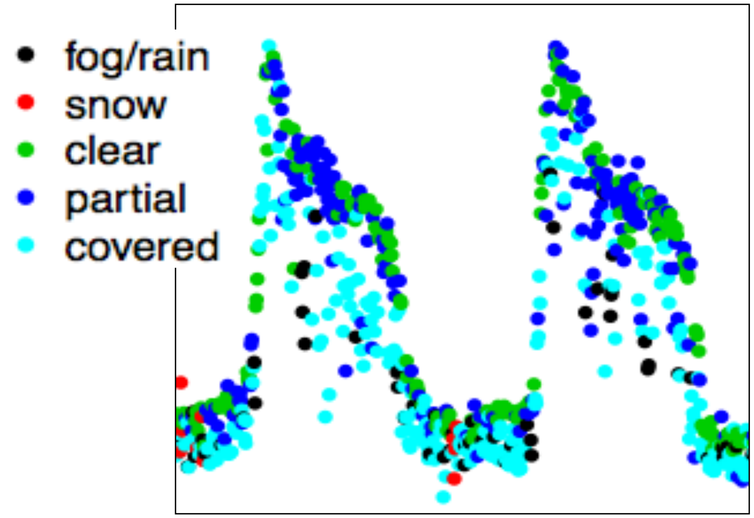


Different shape of EVI and camera Greenness trajectories
Sigmoid curves not entirely appropriate characterization
Results in persistent bias in retrieved dates, in particular
camera senescence is much earlier than MODIS

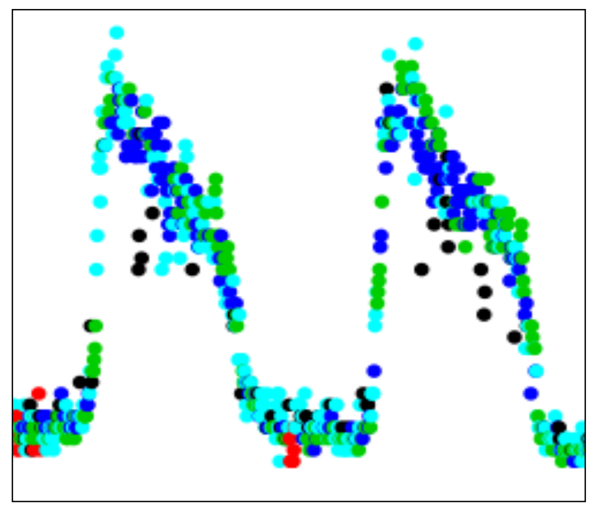


Challenge #1:
Filtering and QA/QC

- Cameras sensitive to variation in amount and quality of solar radiation (clouds, aerosols, precipitation, solar elevation)
- Need to understand in-camera processing, causes of day-to-day variability
  - Rain, fog and heavy cloud cover result in more blueness, less greenness
- Working on filtering, smoothing, and averaging procedures (multiple images every day – which to include?)
- Not all cameras the same!
- Potential for working in other color spaces (e.g. HSV)



Green excess index

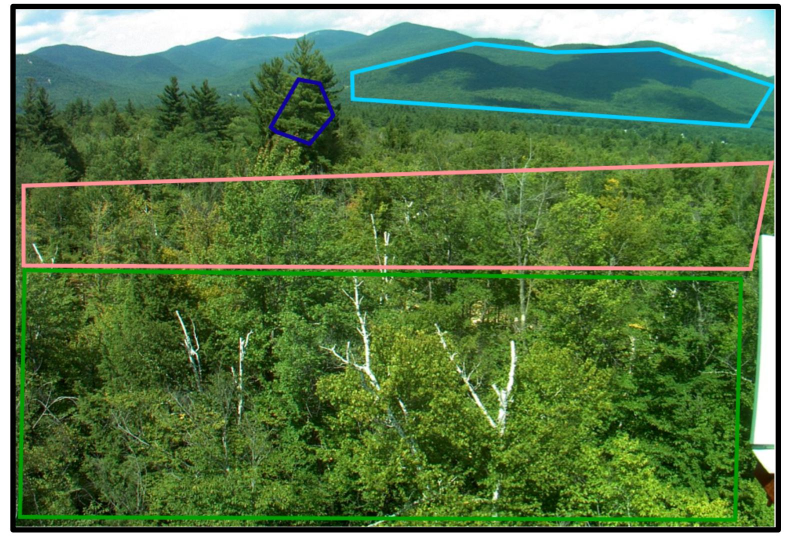


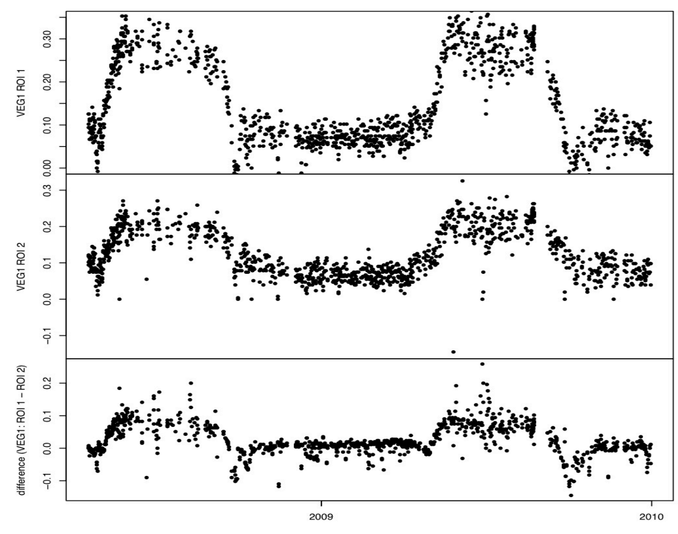
Relative green index

Challenge #2:

Upscaling from Leaves to Pixels

- Camera field of view not the same as MODIS pixel
- Differences within and among deciduous species in terms of timing, rate, and amount of peak greenness
- Larger differences between deciduous and evergreen
- Selection of ROI is important
- Need to develop logic for scaling camera field of view to 500 m (or larger) pixels

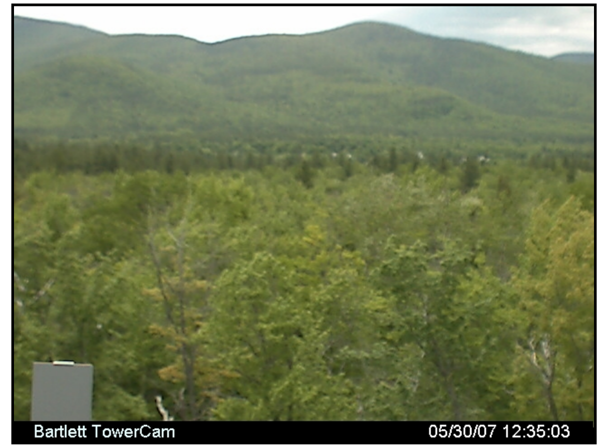


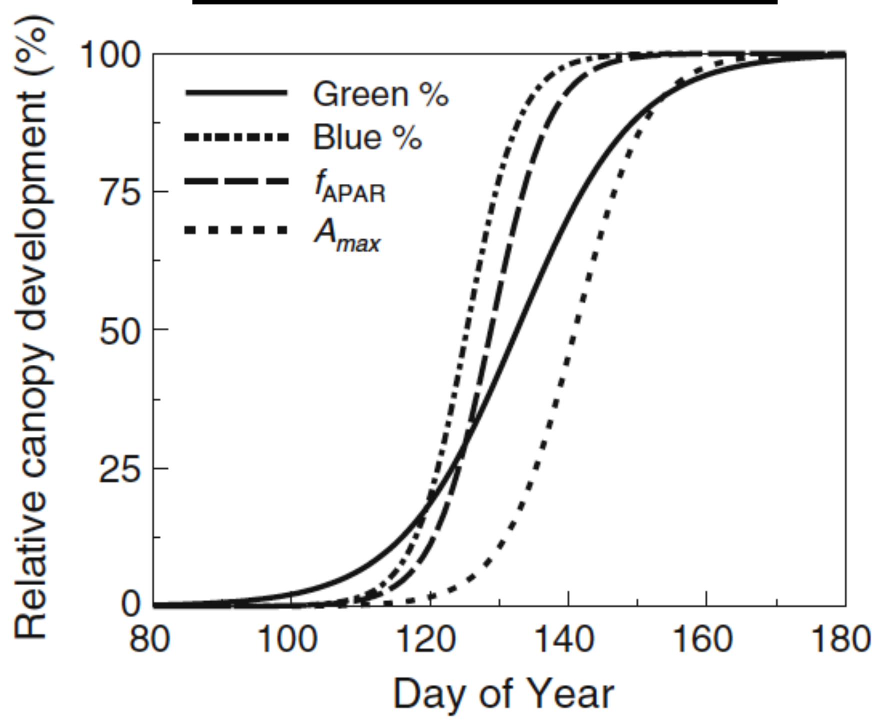


Challenge #3:

Which index tells us what we want to know?

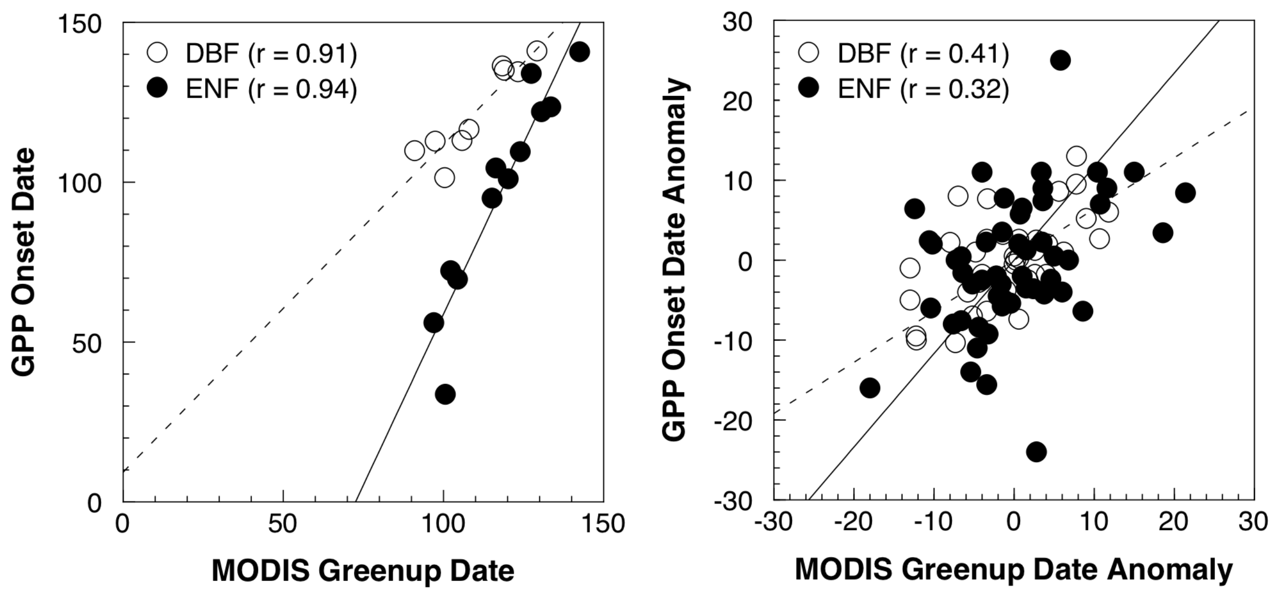
- Phase and velocity of seasonal trajectory depends on the metric
- Canopy greenness and light interception do not parallel each other
- Photosynthesis (from tower fluxes) lags canopy development
- What are we really trying to observe or quantify?
- What question are we really trying to answer?





FLUXNET as a Potential LPV Data Source

Phenology of Ecosystem Processes: FLUXNET GPP vs. MODIS Phenology



- First/last dates of photosynthesis extracted from FLUXNET database for 21 winter dormant temperate and boreal sites with 5+ years of data
- Spatial patterns: high correlation (GPP onset and MODIS greenup
- Temporal patterns: low correlation between GPP onset and MODIS greenup (but statistically significant)
- Links between MODIS and tower GPP not clearly defined in autumn
- Some FLUXNET sites also measure f_{APAR}, albedo, broadband NDVI…

Looking ahead

Conclusions and recommendations

- Satellite data potentially invaluable source of information about spatial and temporal variability in vegetation phenology
- Previous analyses have generally used metrics or indices with large and poorly quantified uncertainties, particularly with respect to what these correspond to on the ground (assessment of accuracy and precision greatly needed)
- Community consensus needed
  - we are trying to quantify (overall trajectory? transition dates?)
  - what are the appropriate validation data? (cameras? field observations?)
- Spatio-temporal variability is essential for testing products
- Uncertainties appear particularly large in autumn, when there is little agreement between satellite and camera-based metrics
- Possibilities of other reference data sources, e.g. FLUXNET (new data sharing policy - http://www.fluxdata.org/)?

Phenology in the New Millennium

- ***New vision of the importance of phenology***:
  - Highly sensitive to **global change**: "Phenology … is perhaps the simplest process in which to track changes in the ecology of species in response to climate change" (IPCC AR4: *Climate Change 2007 – Impacts, Adaptation and Vulnerability,* page 99)
  - **Feedbacks** to the **climate** system (albedo, surface energy balance, CO_2 exchange, VOCs)
  - Factor in **ecological interactions** (productivity, competition, pollination, seed dispersal)
  - Relevance for land **management** (agriculture, forestry, invasive plants and pests) and human health (transport of allergens and disease vectors)
- Greater emphasis on **new types of data** and phenological indicators (satellite remote sensing, atmospheric CO_2 concentrations, tower CO_2/ H_2O fluxes, webcam imagery) and standardized protocols for ground observations (e.g. USA-NPN)