Satellite observations of Amazon phenology in response to climate, landscape, and anthropogenic forcings

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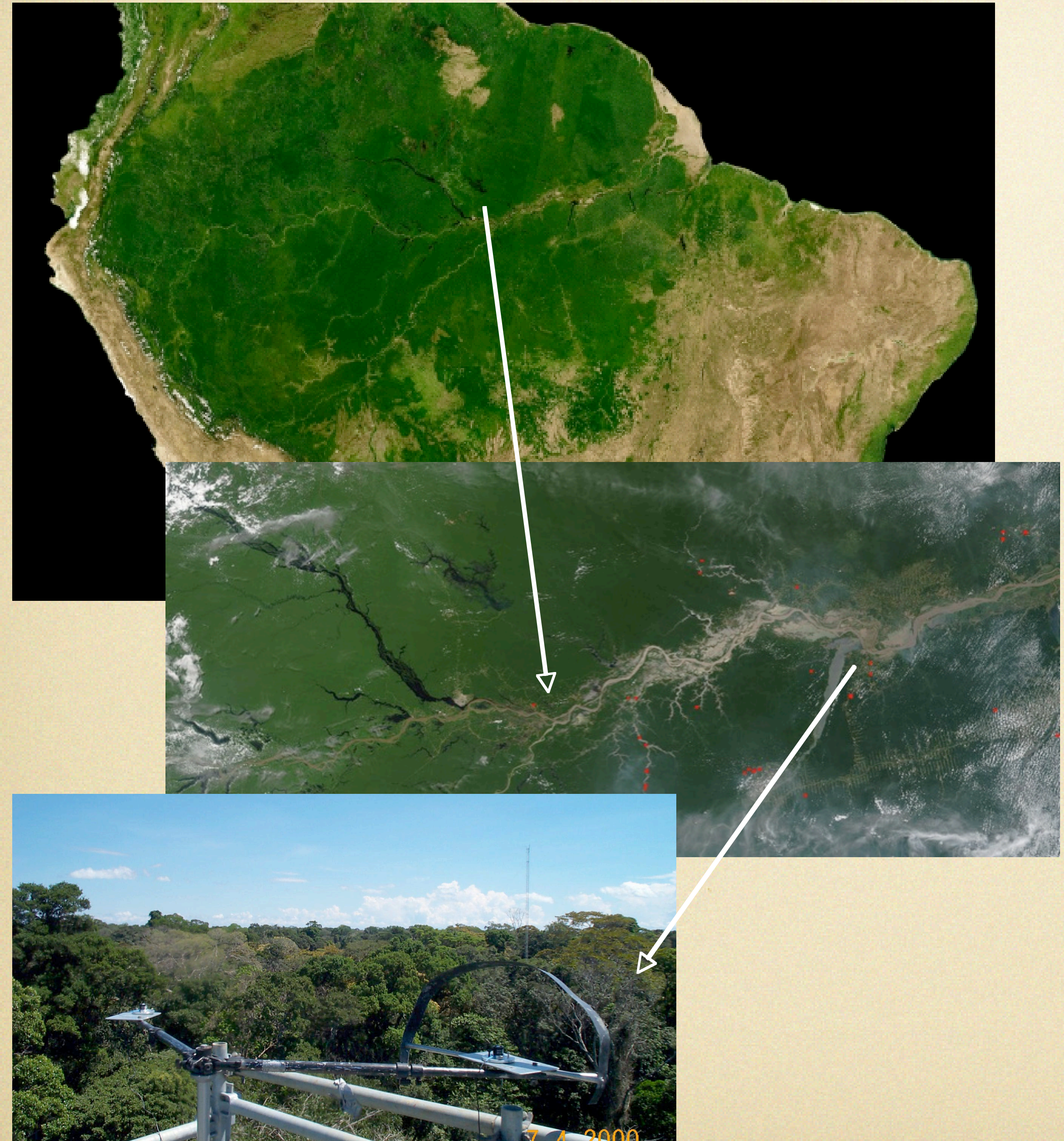
Introduction

- The rainforests of the Amazon basin form the largest contiguous, intact tropical forest on Earth, a vast storehouse of carbon that could influence the trajectory of global climate change.
- Tropical forest ecosystems also have social, cultural and economic significance as sources of important renewable and non-renewable resources.

- The functional behavior of tropical forest ecosystems are not well understood,
- Present-day metabolism and carbon balance of Amazonia remains poorly characterized due to complex environmental controls (moisture, sunlight) and associated biologic responses.



Knowledge of the temporal dynamics and spatial heterogeneities of tropical forest ecosystems at multiple scales is necessary to understand vegetation behavior and in understanding how plants might adapt to global change.

Phenology

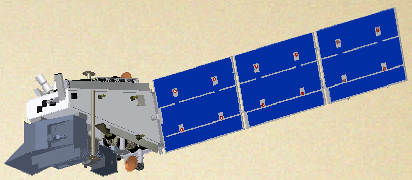
- At the landscape level, many climate and growth models characterize tropical evergreen rainforests as having no seasonal variation in biophysical plant properties such as greenness, leaf area index, FAPAR, and albedo
- Coarse resolution, multi-temporal satellite measurements, such as the NOAA-AVHRR time series data, are widely used for large scale vegetation monitoring and vegetation -climate studies, however, such data have also treated the phenology of tropical evergreen forests as flat or seasonally constant.
- Finer resolution satellite data (e.g. Landsat) offer more accurate monitoring and discrimination of tropical forests and disturbance events, such as deforestation and fire. However, it is difficult to obtain cloud-free images at the frequencies needed to define accurate phenology trends.

Uncertainties

- Satellites can provide consistent measures of vegetation activity with spatial- and temporal- detail at the global scale, which can be linked to ecosystem health, productivity and carbon fluxes,
- There remains large uncertainties in estimating GPP at the canopy level associated with
  - Seasonal dynamics
  - Spatial variation due to climate, soils, and land use (disturbance, management,…)
- Uncertainties associated with coarse scale meteorology, remote sensing variables (LAI, FPAR, VI), and canopy biophysical attributes (land cover type, biome-specific, disturbance history)

Heinsch et al., 2006

Objectives



- Assess spatial and temporal variability in vegetation activity in tropical forest ecosystems
- Assess the influences of light, moisture, and human activity in tropical forests
  - Changes in phenological metrics depict a canopies' integrated response to environmental change,
- Test for phenologic consistencies of satellite data with flux tower data in highly impacted/ disturbed tropical forests in Asia

Mechanisms controlling phenology

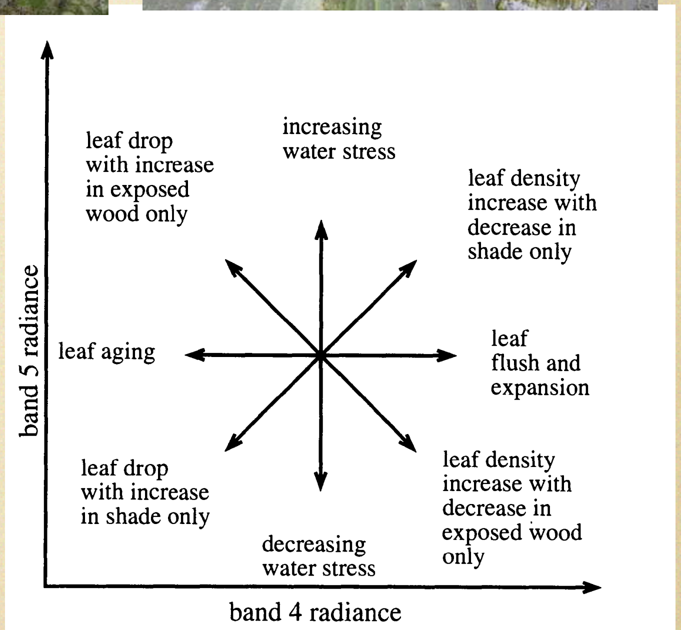
- However, plot-level & flux tower local-scale studies have observed consistent seasonal changes in tropical forest canopy characteristics, including synchronized flushing and exchange of new leaves, periods of decreased foliage density, leaf aging, senescence, and litterfall in response to common environmental factors, such as rainfall, temperature, and photoperiod (Wright and Schaik, 1994; Reich et al., 2004; Saleska et al., 2005)

- Leaf and flower production in many rainforests, including central Amazônia have been reported to closely coincide with dry season peaks in incident photosynthetic active radiation (PAR) [Wright & van Schaik 1994].

Leaf flushing with sunlight at Tapajós, July 2002 (photo by Tomoaki Miura)

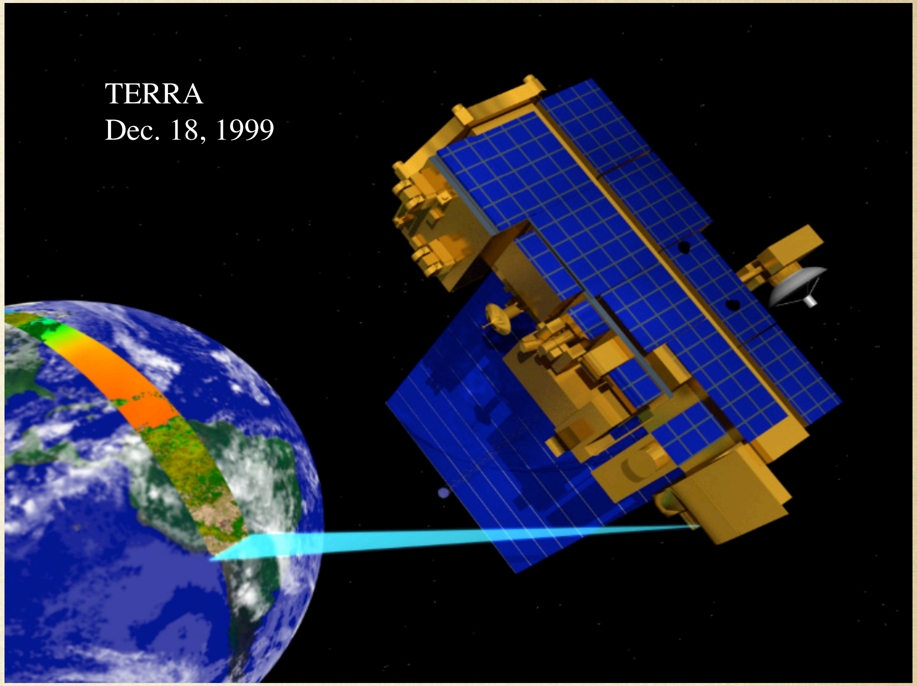
Phenologic-optical Changes in Tropical Forests

- Leaf aging
- Epiphylls
- Litterfall
- Leaf flushing & expansion
- Leaf density, exposed wood & soil
- Canopy shade, light & gaps
- Leaf water stress
- Upper and lower leaves



Bohlman et al., Biotropica 30 (1998)

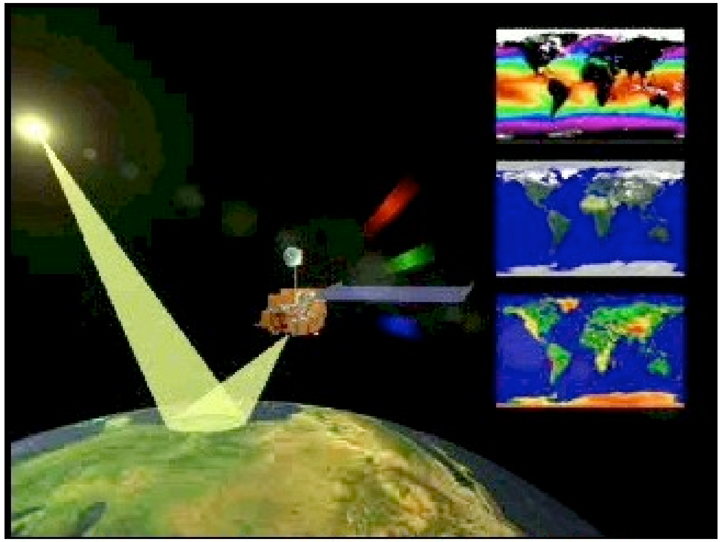
- Recent satellite observations are providing new opportunities to map and better understand spatial patterns of landscape phenology and productivity as a function of environmental controls and land use activities.



Terra- MODIS data

We investigated the phenology of Amazon ecosystems across over a range of climate (precipitation, light) and land use conditions encompassing open and dense moist rainforests, seasonally dry forests, ecotone forests, regenerating forests, and converted pasture/ agriculture with satellite observations from fine resolution EO-1 Hyperion and moderate resolution MODIS

Terra- MODIS Vegetation Index Product (MOD13Q1, A2)

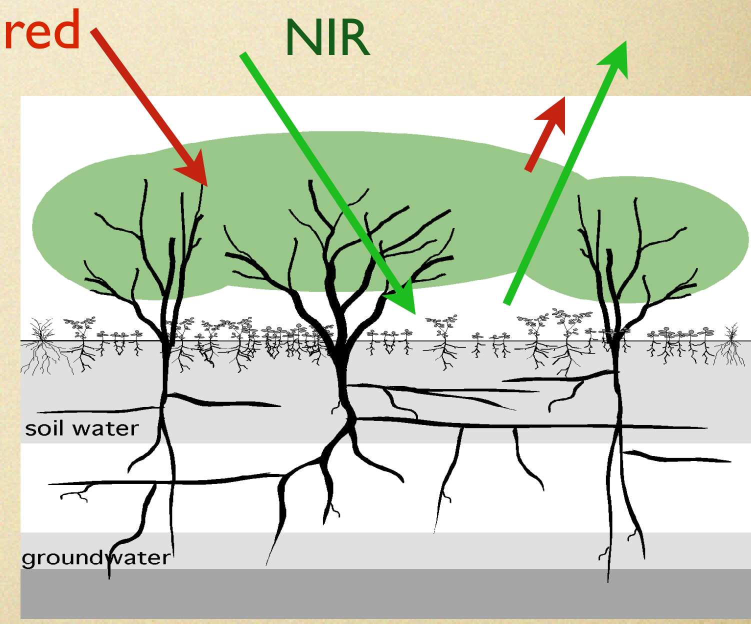


The derivation of thematic data from Earth observing satellites.

Enhanced Vegetation Index

$$EVI = G \times \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + C_1 \times \rho_{red} - C_2 \times \rho_{blue} + L}$$

- Based on 1st-order Beer's law application of radiative transfer in canopy
- Extends sensitivity in high biomass canopies and removes soil optical influences



Travis Huxman

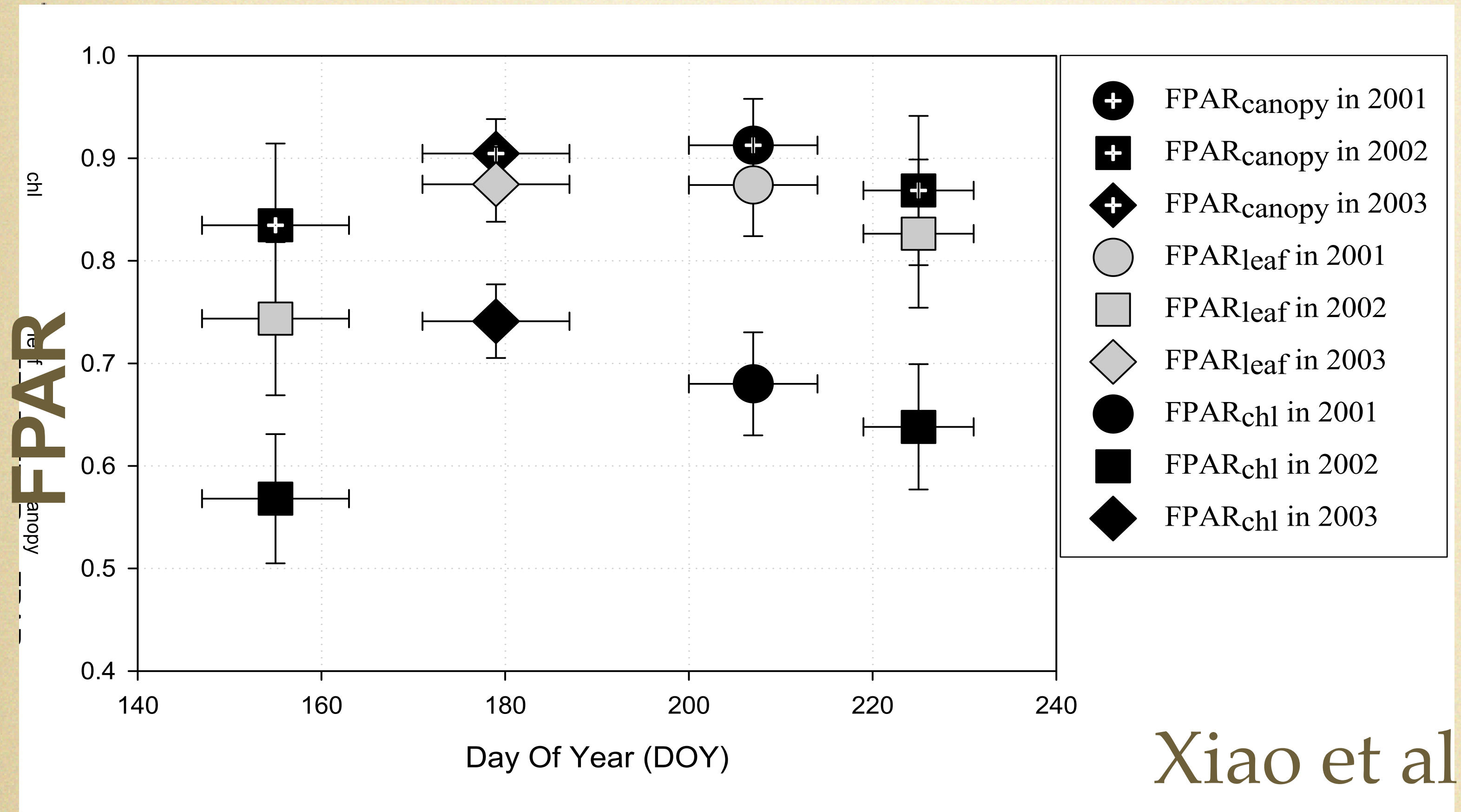
Conversion of VI to FPAR?

- Most common method to derive FPAR is through NDVI relationships
- Only PAR absorbed by chlorophyll is responsible for photosynthesis:
  - $FPAR_{canopy} = FPAR_{chl} + FPAR_{NPV}$

- Comparisons of $FPAR_{chl}$ and $FPAR_{canopy}$ would help define to what degree the PEM models are consistent with light absorption process of photosynthesis at the chlorophyll level.

$FPAR_{canopy}$, $FPAR_{leaf}$, and $FPAR_{chl}$

deciduous broadleaf forest (Harvard Forest)



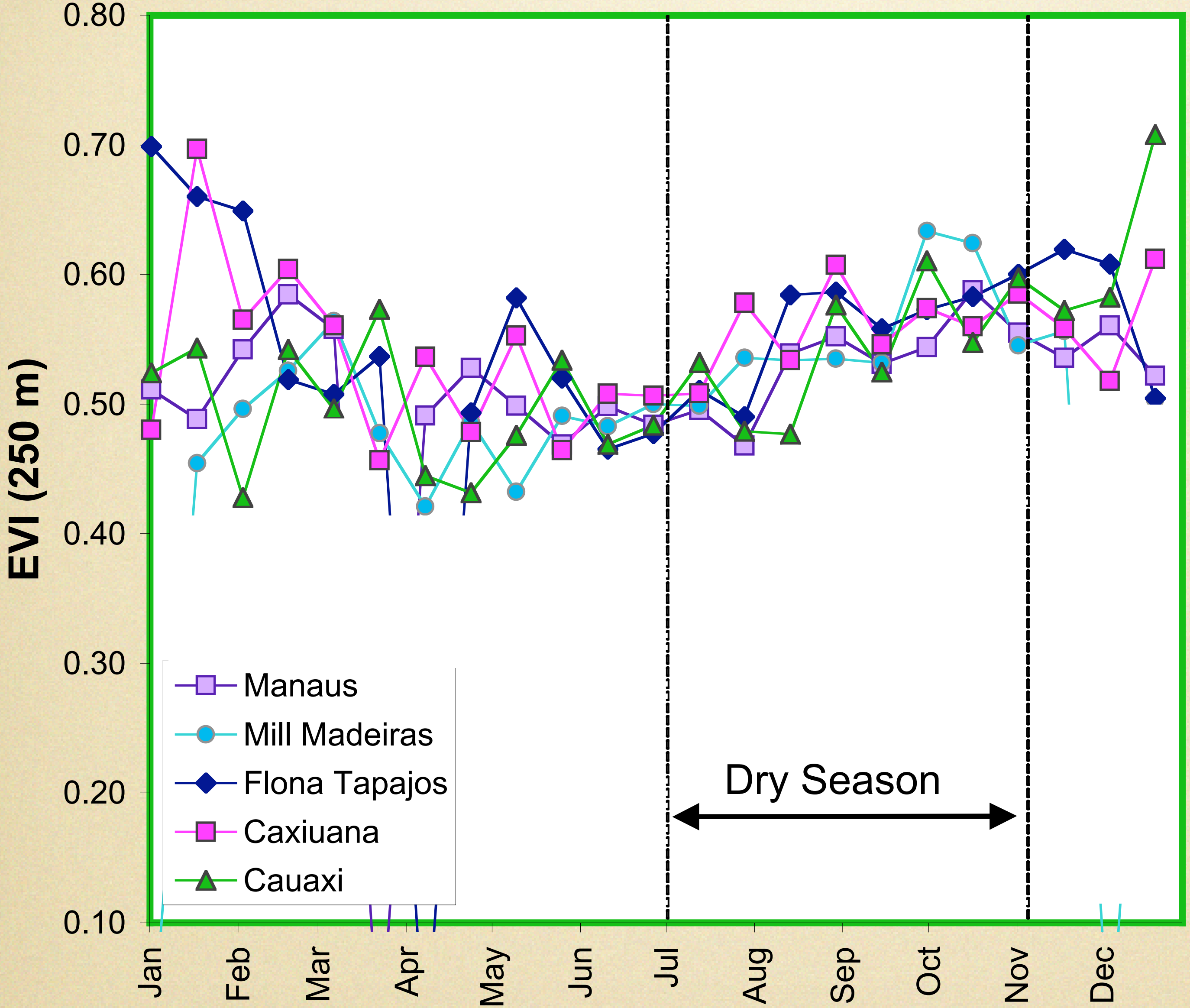
Xiao et al. 2005, 2005

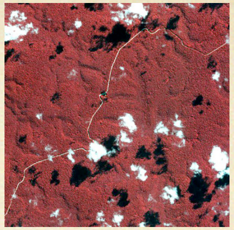
$FPAR_{leaf} = f(NDVI)$

$FPAR_{chl} = f(EVI)$

Zhang et al.,2005, using a radiative transfer model (PROSAIL2) & daily MODIS data

Site Results

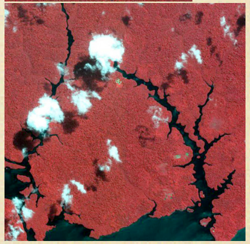




Manaus

Mill Madeiras

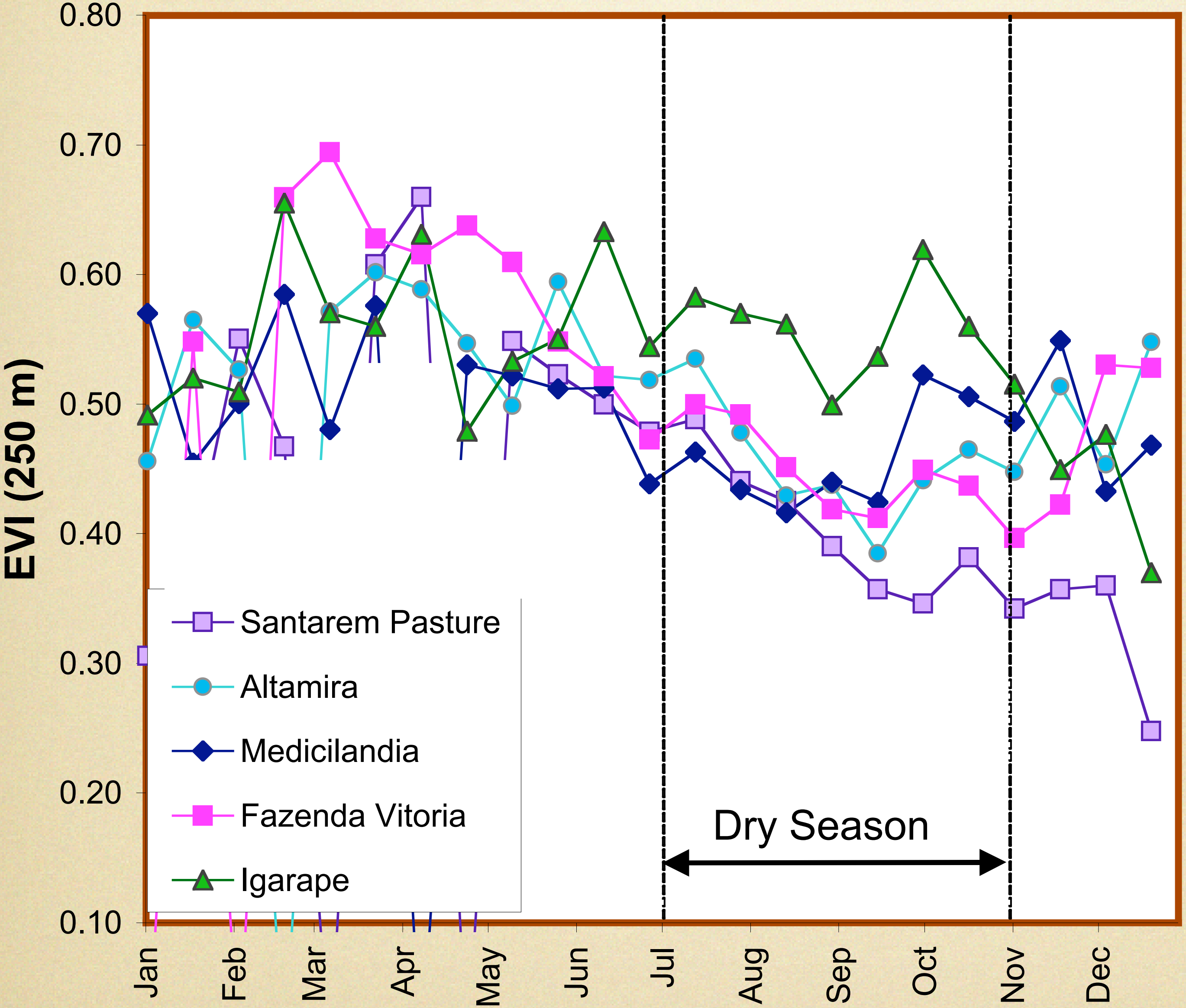
Flona Tapajos



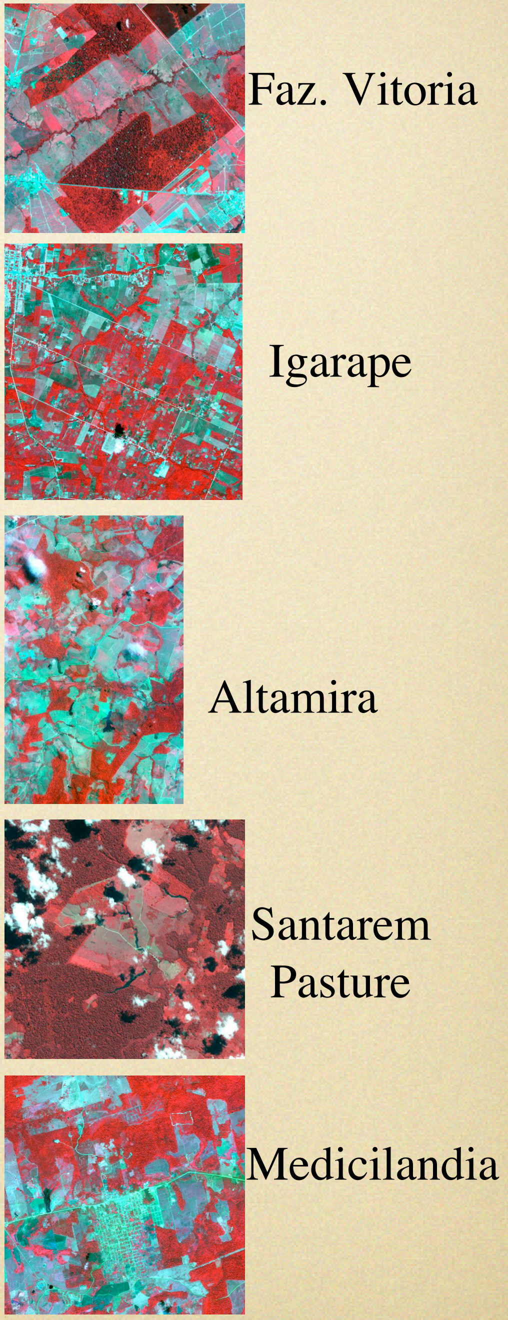
Caxiuana

Cauaxi

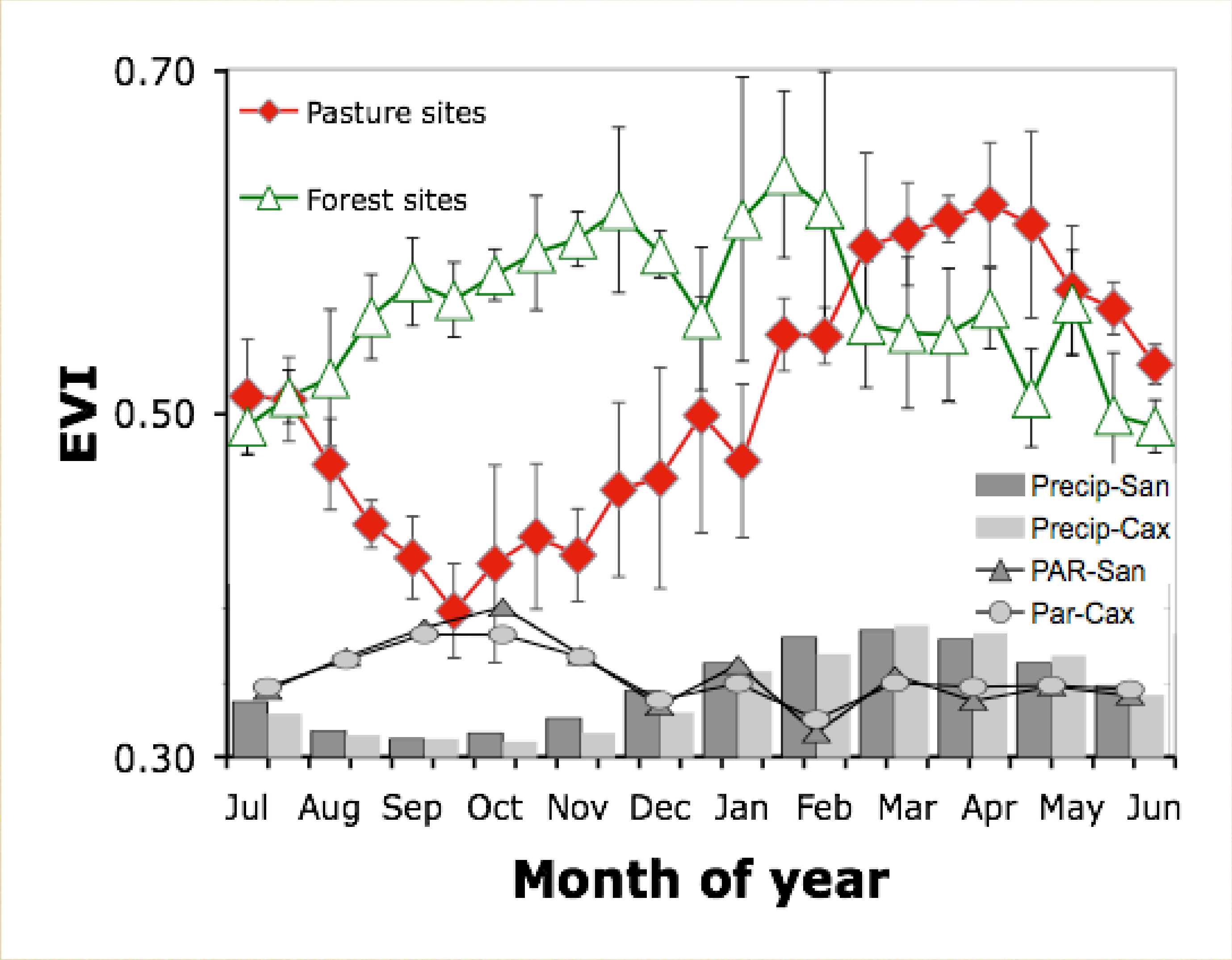
Pastures

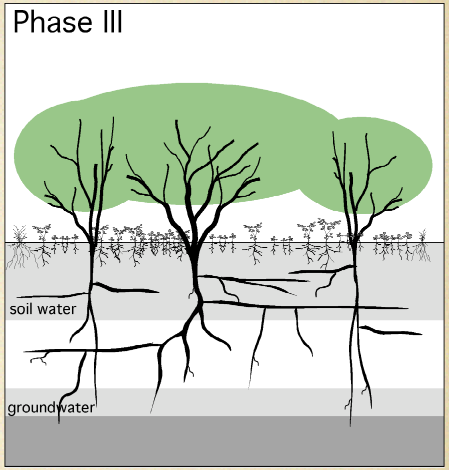


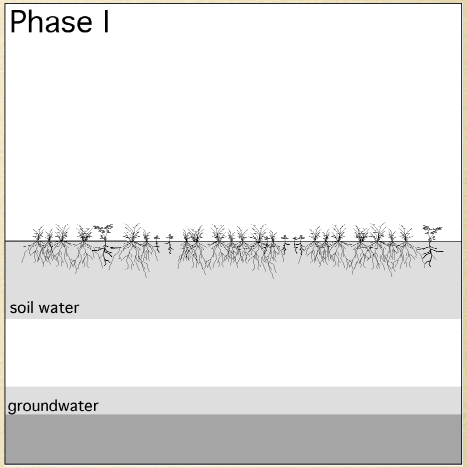
EVI (250 m)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Santarem Pasture
Altamira
Medicilandia
Fazenda Vitoria
Igarape
Dry Season



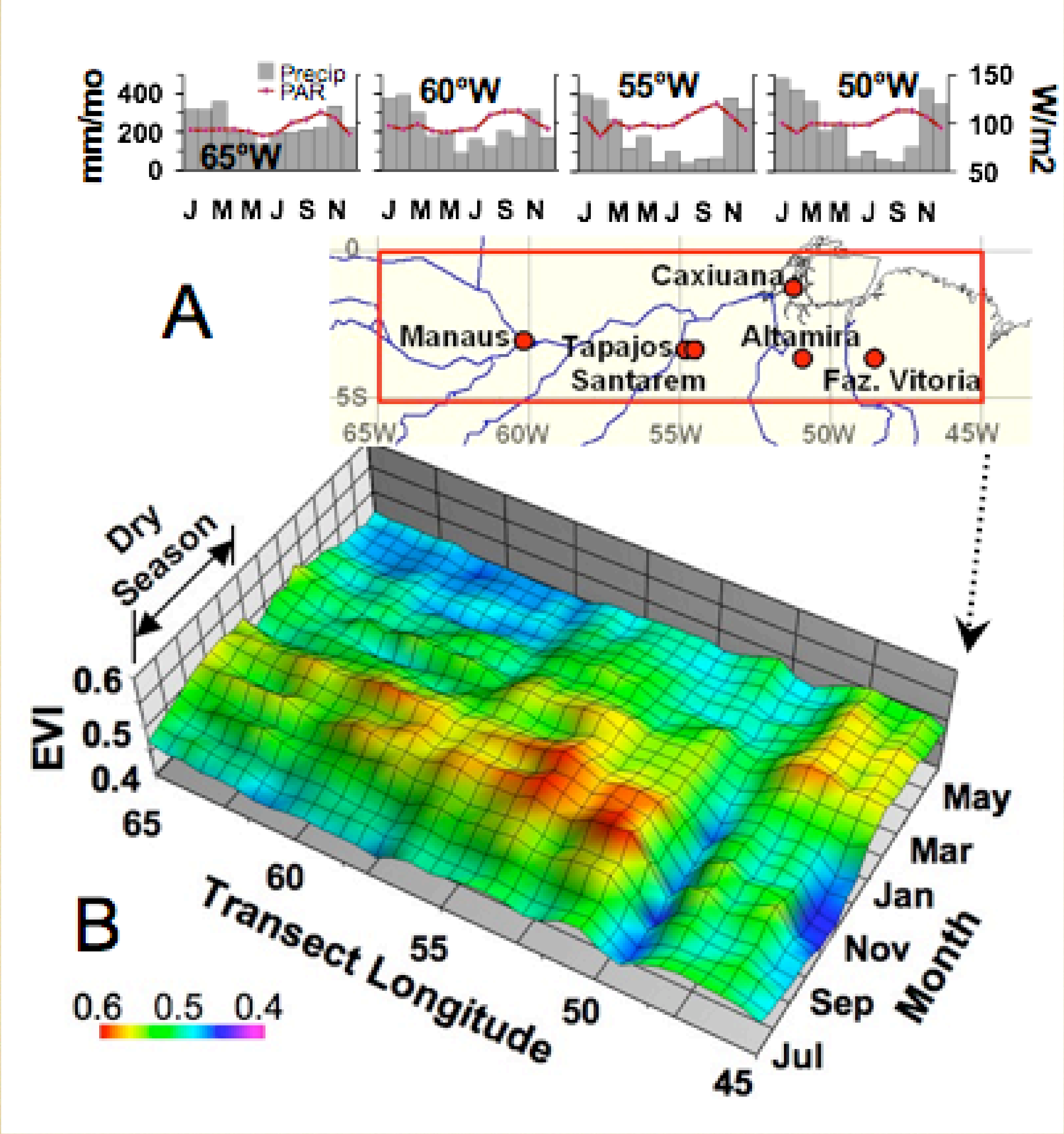
Faz. Vitoria
Igarape
Altamira
Santarem Pasture
Medicilandia





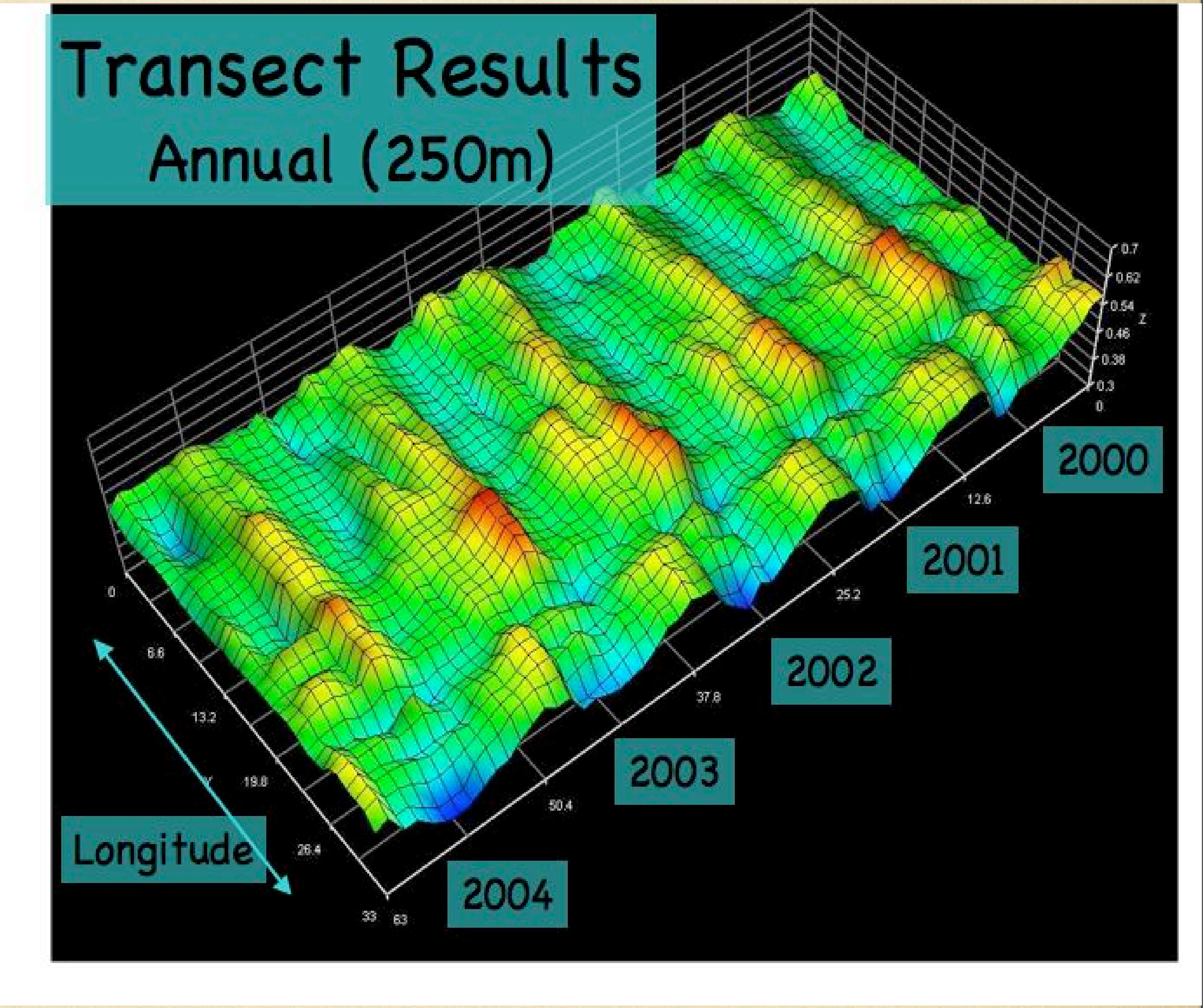


Amazon Basin: Sunny dry season 'green-up" is reversed in disturbed areas (shallower rooting systems)

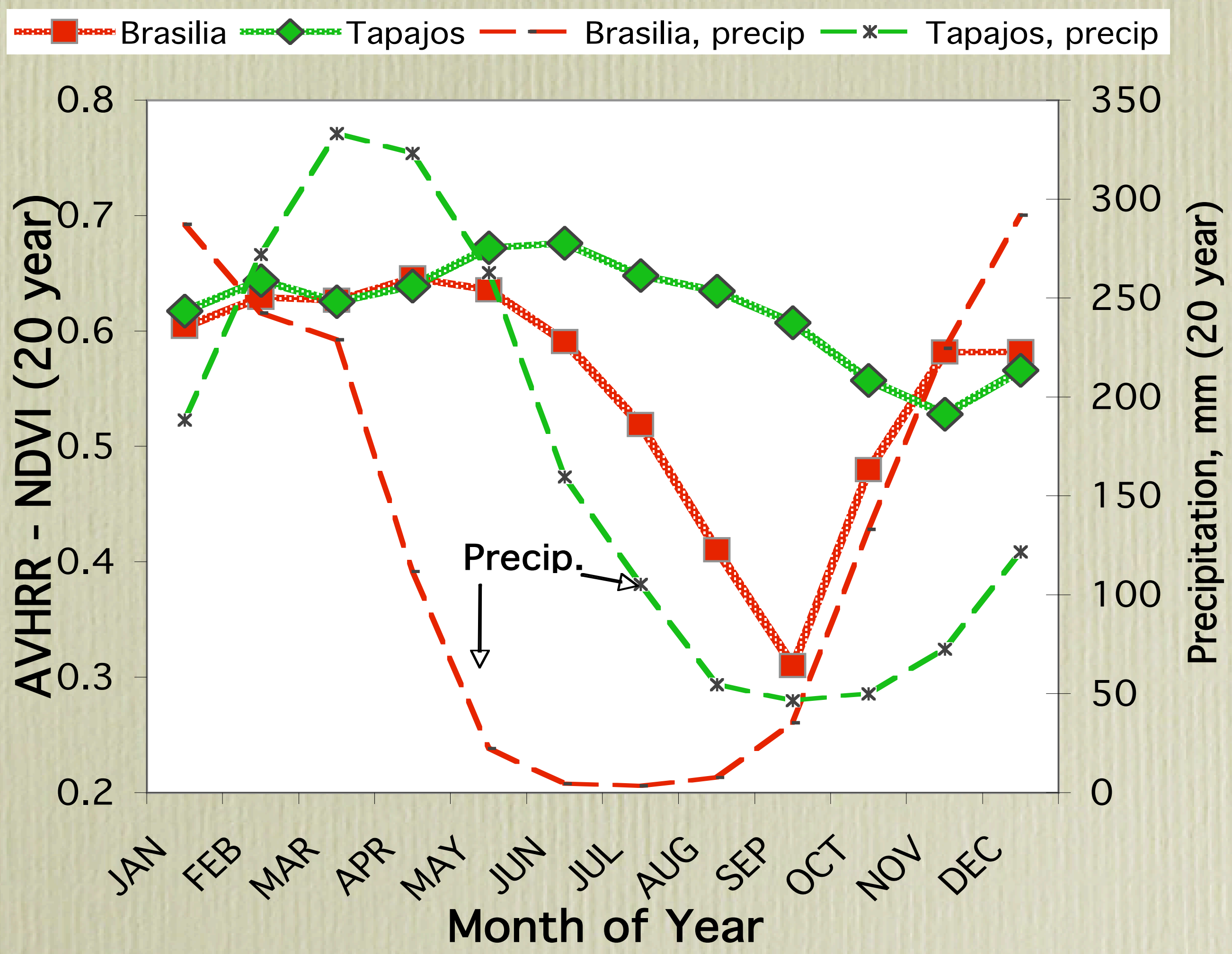


Precip
PAR
mm/mo
400
200
0
65°W
60°W
55°W
50°W
150
100
50
W/m2
J M M J S N
A
Caxiuana
Manaus
Tapajos
Santarem
Altamira
Faz. Vitoria
0
-5S
65W
60W
55W
50W
45W
Dry Season
EVI
0.6
0.5
0.4
65
60
55
50
45
Transect Longitude
May
Mar
Jan
Nov
Sep
Jul
Month
B
0.6 0.5 0.4

MODIS shows tropical rainforests as having significant seasonal variation in vegetation dynamics.



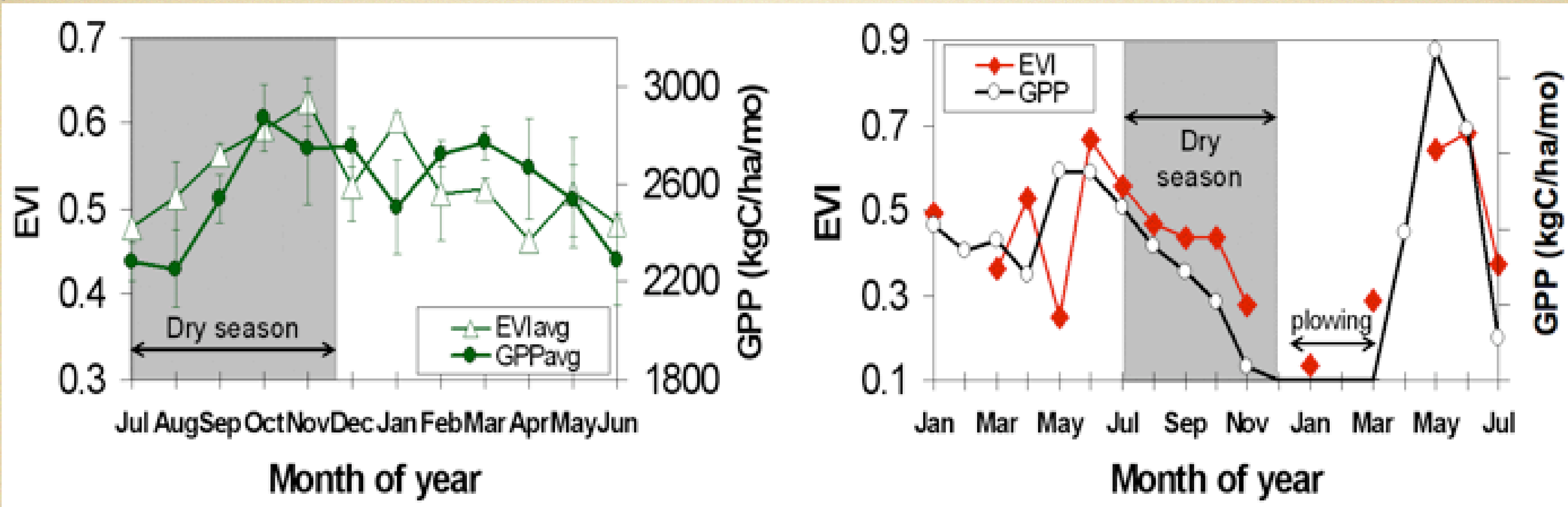
NOAA- Advanced Very High Resolution Radiometer (AVHRR) in the Amazon



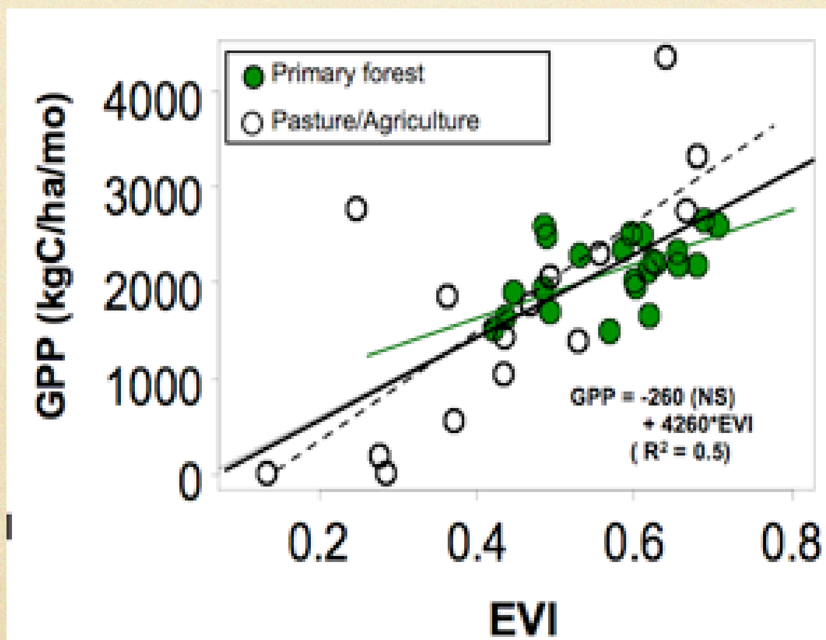
Barbosa, H.

Coupling of satellite data with in-situ networks (eddy-covariance flux towers)

- **"Integration of in situ, airborne and space-based observations within the various societal benefit areas will be encouraged, as will the establishment of global, efficient, and representative networks of in situ observation to support process studies, satellite data validation....," (GEOSS)**
- Continuous measurements of flux (CO_2, H_2O, heat and momentum) data are powerfully suited for vegetation dynamics and for deriving relationships between carbon fluxes and key driving variables.
- Can test model/remote-sensing estimates of carbon-exchange and seasonality.

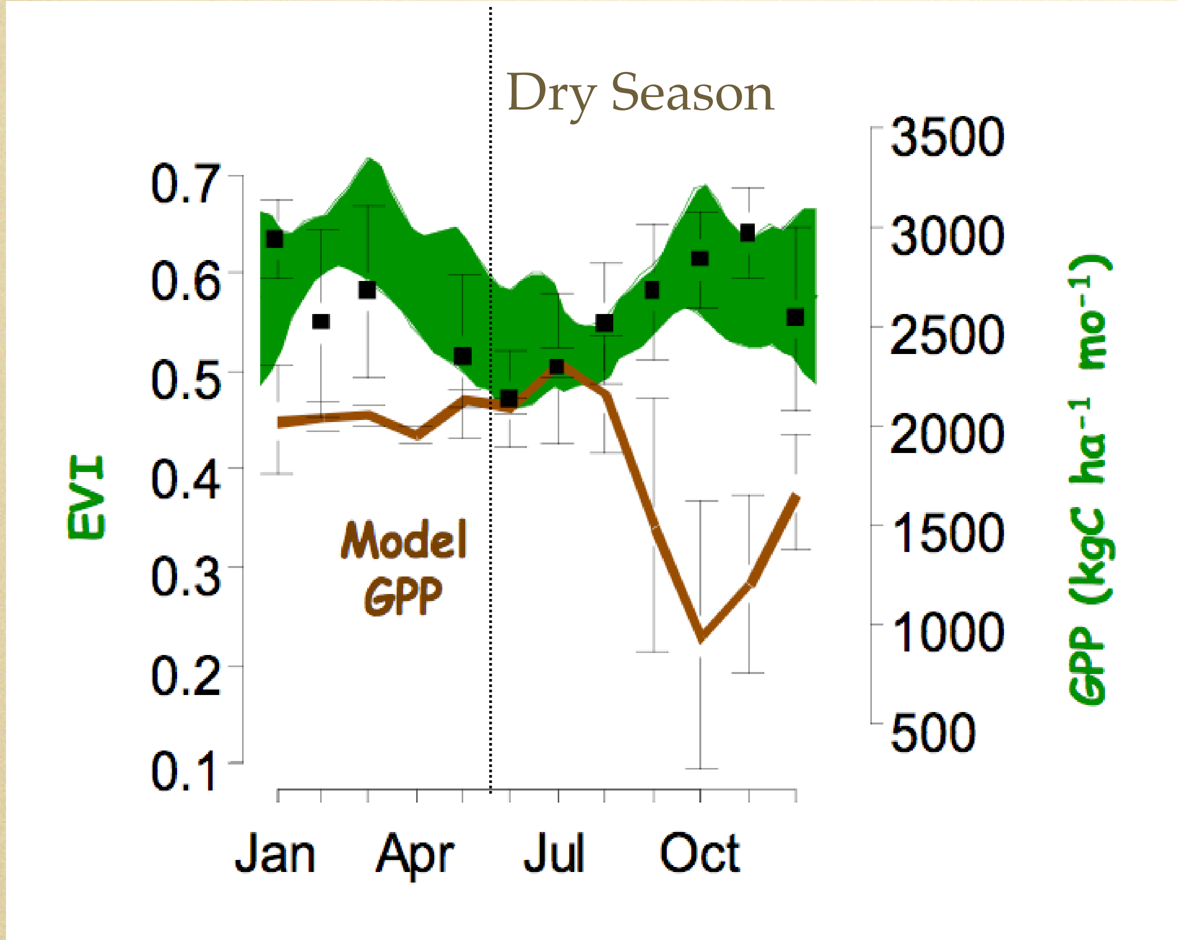


Tapajos Forest



Huete et al., GRL 2006

Rainforest GPP & EVI with modeled GPP (IBIS)



Tapajós National Forest

GPP from Lucy Hutyra (Harvard Univ)

Local tower flux measurements of gross primary productivity (GPP) and regional satellite observations from the MODIS show seasonal patterns in canopy photosynthesis, or GPP that follow the availability of sunlight, contradicting many ecosystem models that show dry season declines in photosynthesis due to water limitations.

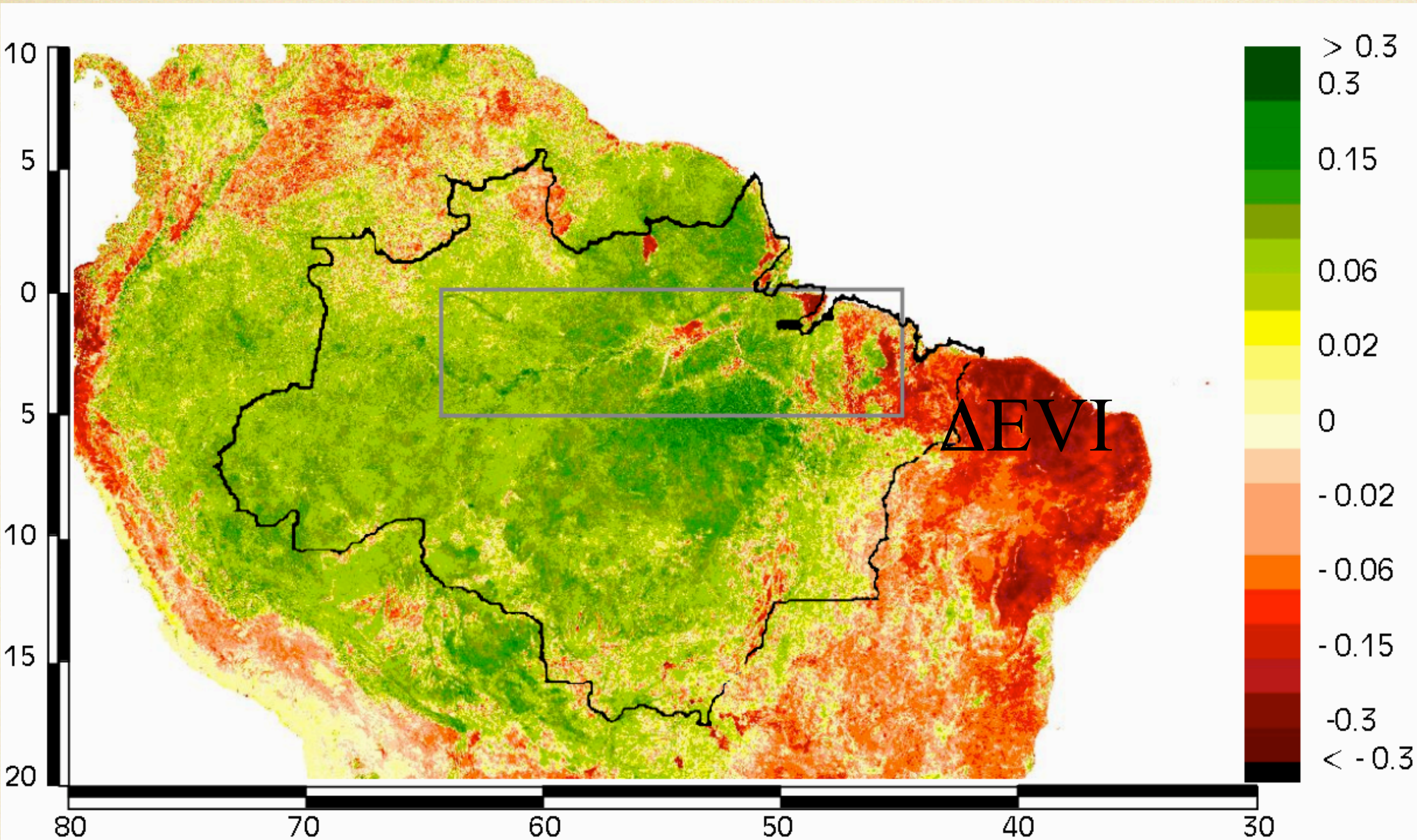
A consistency between independent satellite EVI and tower-derived GPP observations lends confidence to both finding.

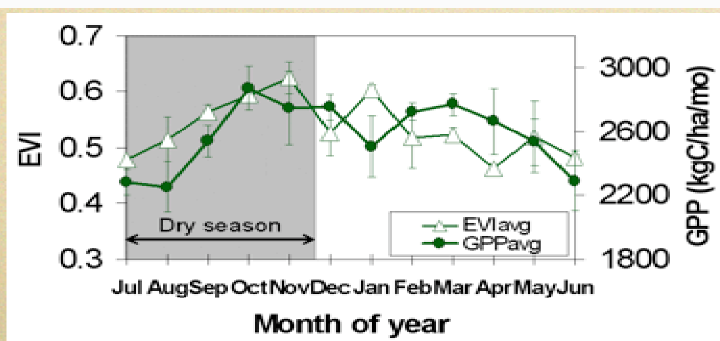
This raises a question about model predictions

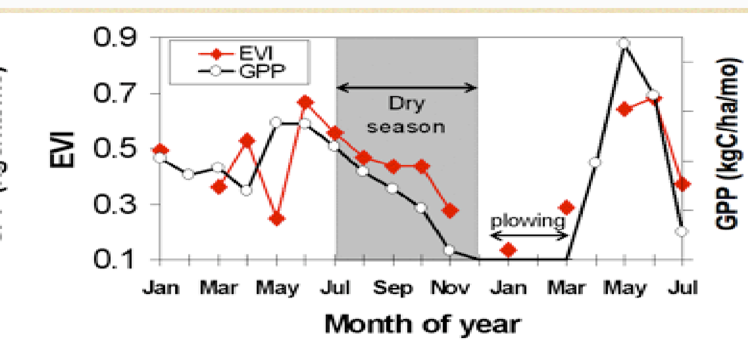
- The same model constructs affect both short-term (seasonal) and long-term variations of C and water exchange,
- but the performance of models at short time-scales (where they can now be tested with data) is problematic, hence affecting confidence in reliability of their long-term predictions?

Basin-wide greening in dry season

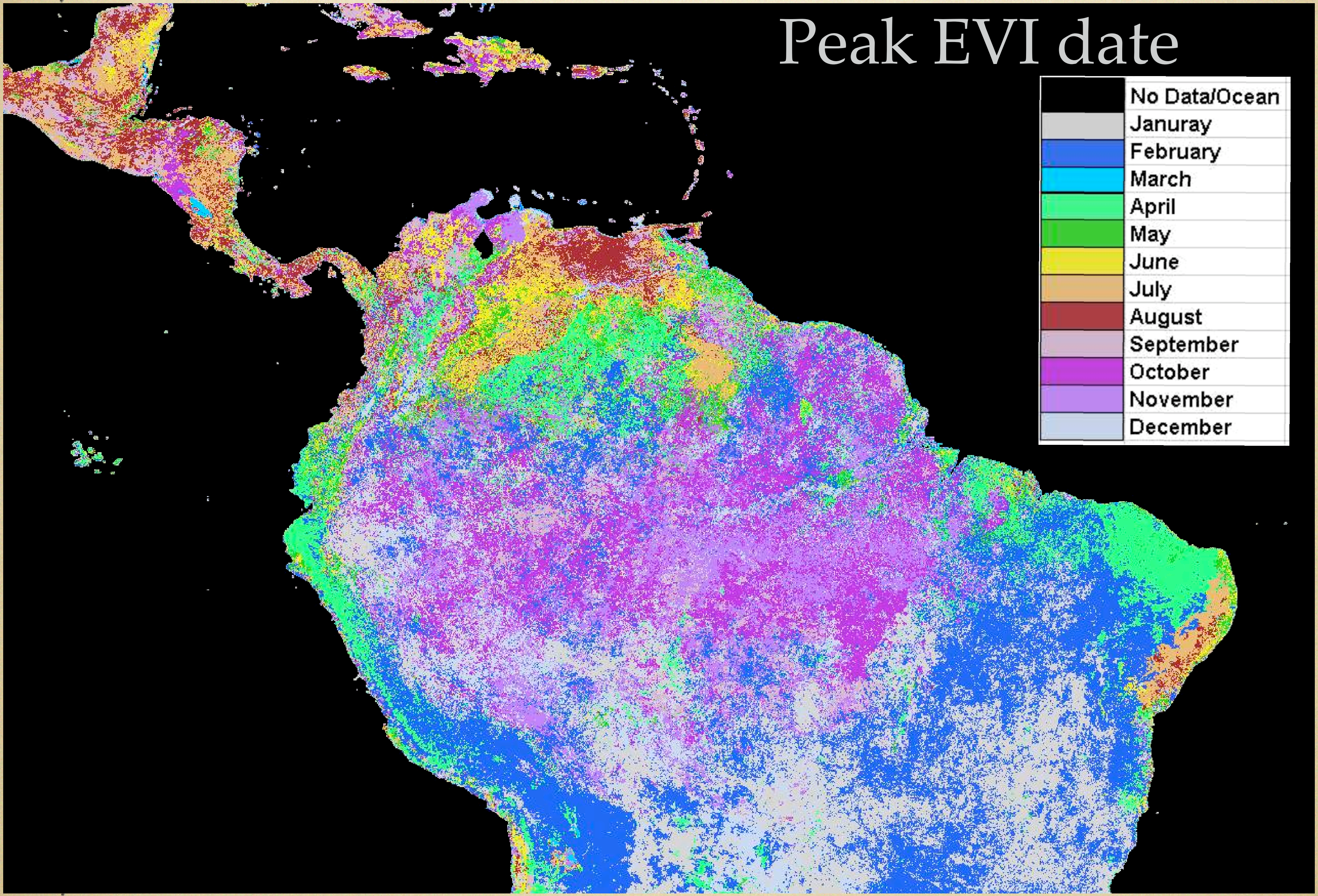
October EVI (dry season) minus June EVI (wet season)



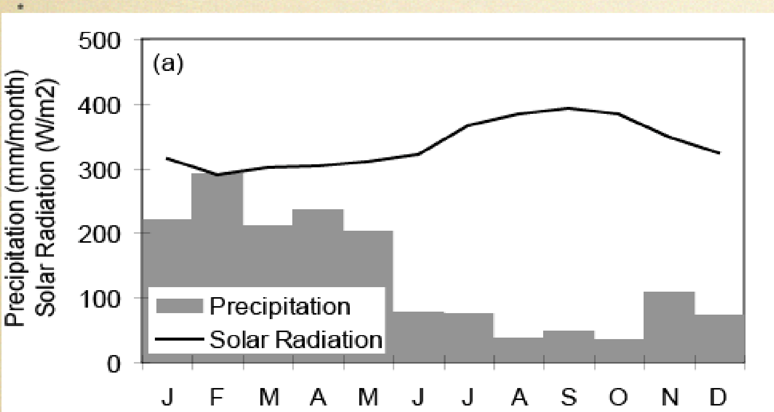


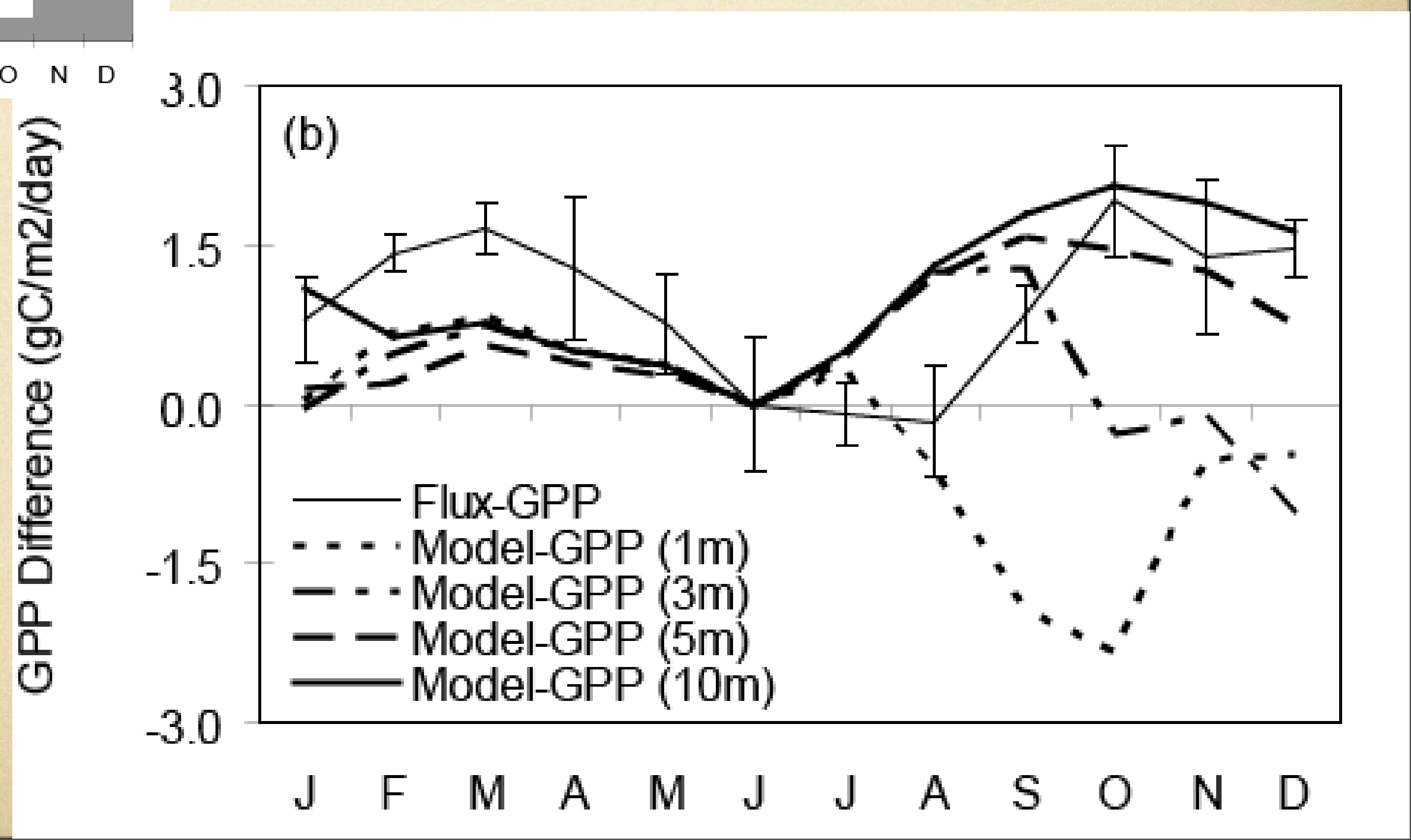


Peak EVI date

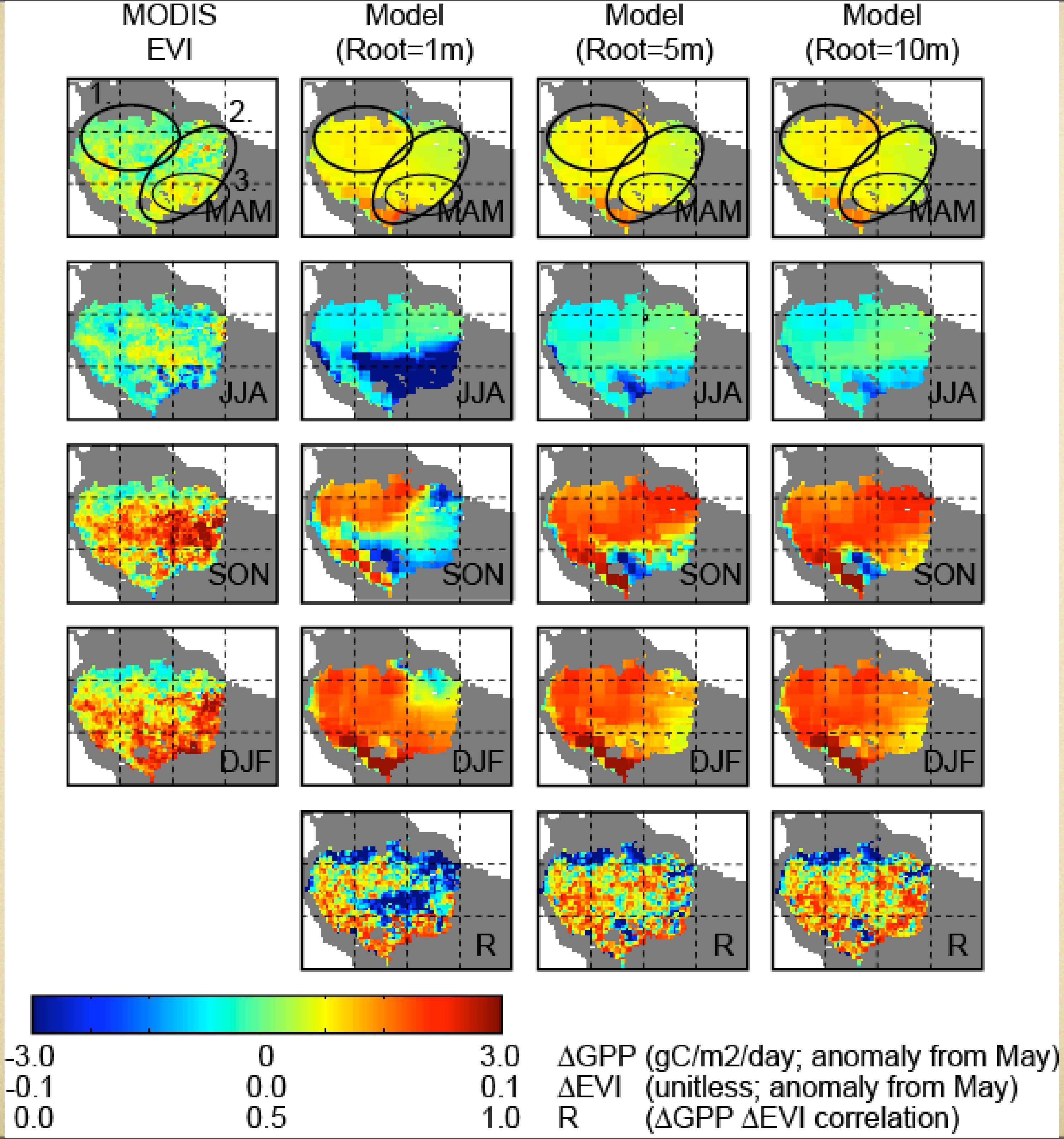


This offers new approaches to constrain rooting depth in terrestrial ecosystem models over the Amazon using MODIS EVI satellite data and Biome-BGC terrestrial ecosystem model.



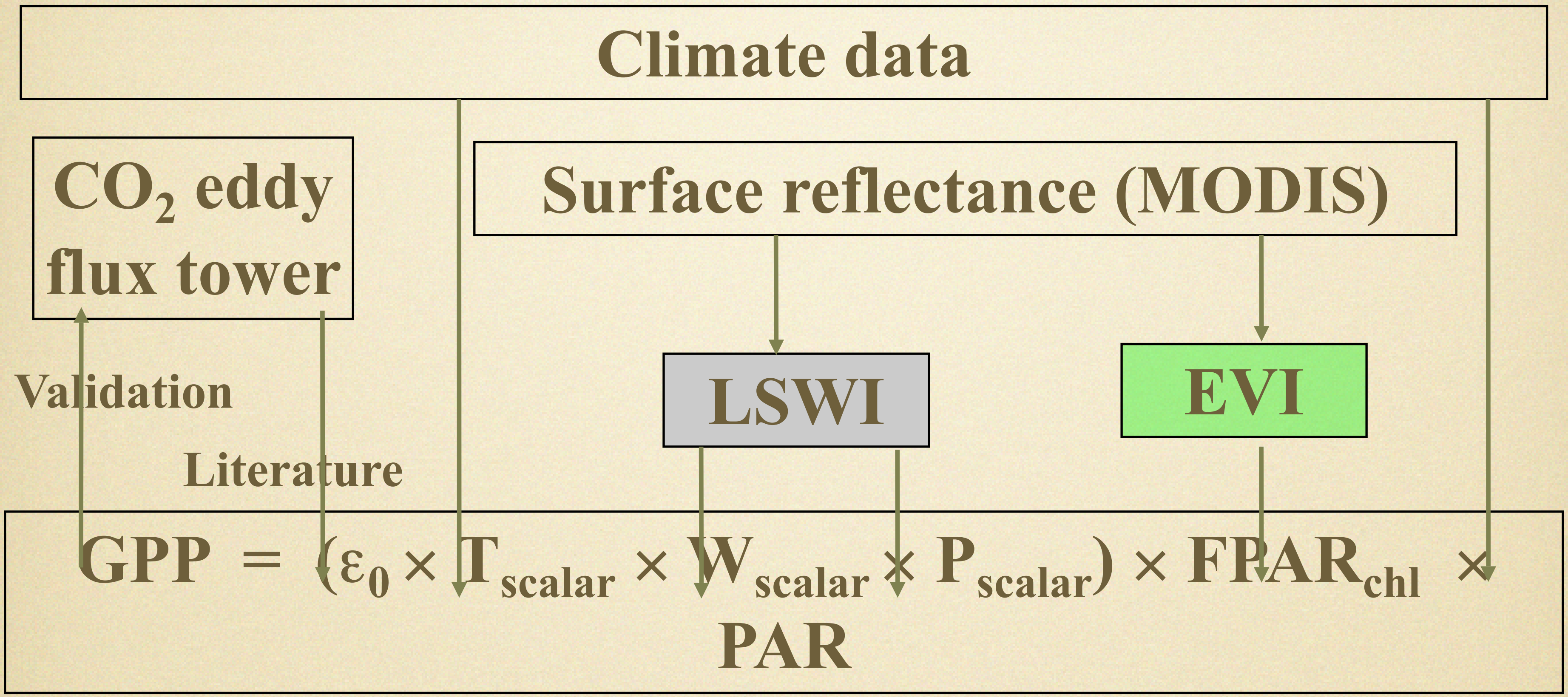


Ichii, et al., GCB, 2006


MODIS EVI
Model (Root=1m)
Model (Root=5m)
Model (Root=10m)
1.
2.
3.
MAM
JJA
SON
DJF
R
-3.0 0 3.0 ΔGPP (gC/m2/day; anomaly from May)
-0.1 0.0 0.1 ΔEVI (unitless; anomaly from May)
0.0 0.5 1.0 R (ΔGPP ΔEVI correlation)

Ichii, K

Satellite-based Vegetation Photosynthesis Model (VPM)



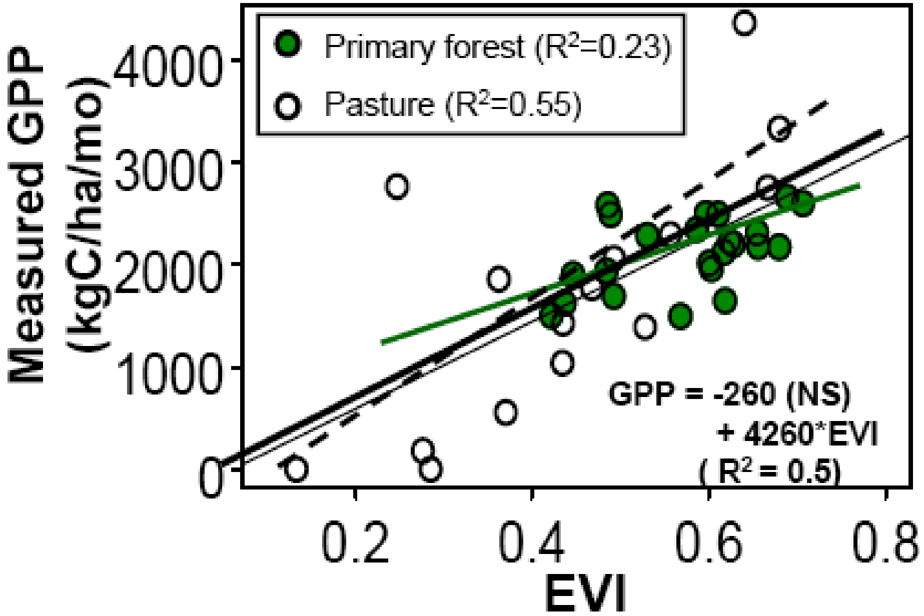
<u>Input data for simulation of the VPM model</u>

Air temperature, PAR, Vegetation indices (EVI, LSWI), Maximum light use efficiency (ε_0)

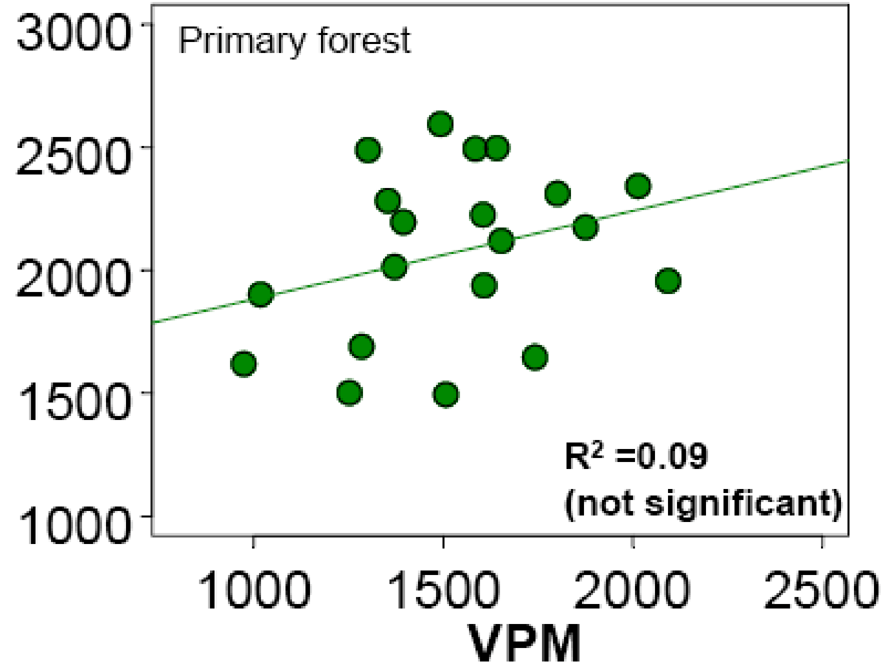
Xiao et al. 2004,2006,2006

Extrapolating tower-derived GPP Carbon fluxes with MODIS remote sensing: unmodified EVI vs. VPM model

GPP versus unmodified EVI
(Huete et al., 2006)



GPP versus EVI-based VPM prediction
(Xiao et al., 2005)



Vegetation-Photosynthesis Model (VPM):
adjusts EVI (photosynthetic infrastructure) by environmental fluctuations:

$$GPP = \varepsilon \cdot T_{scale} \cdot W_{scale} \cdot EVI \cdot PAR$$

Temp scaling — Water scaling — Sunlight

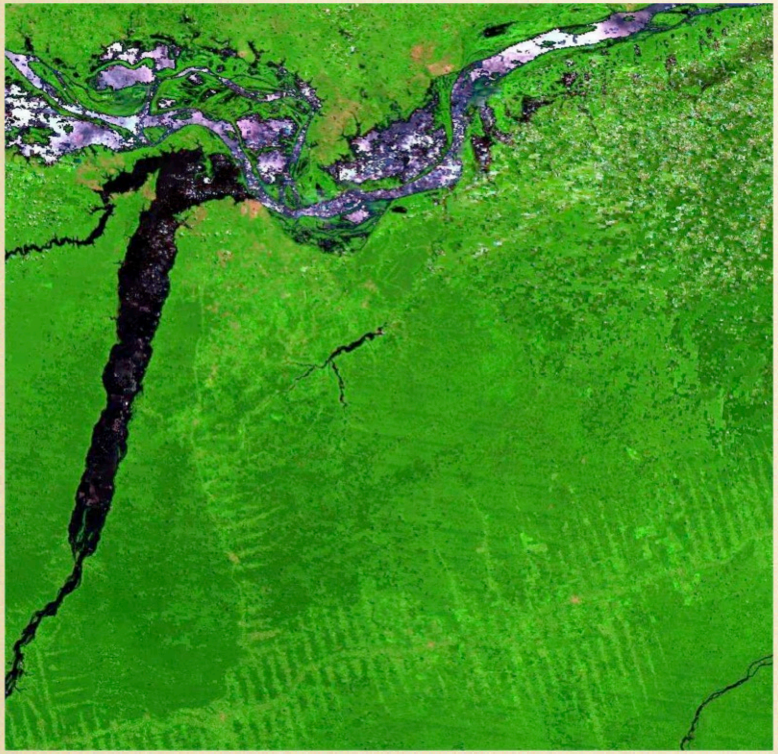
VPM works well in temperate forests (Xiao et al, 2004)

Unmodified EVI works better than VPM in tropical forests

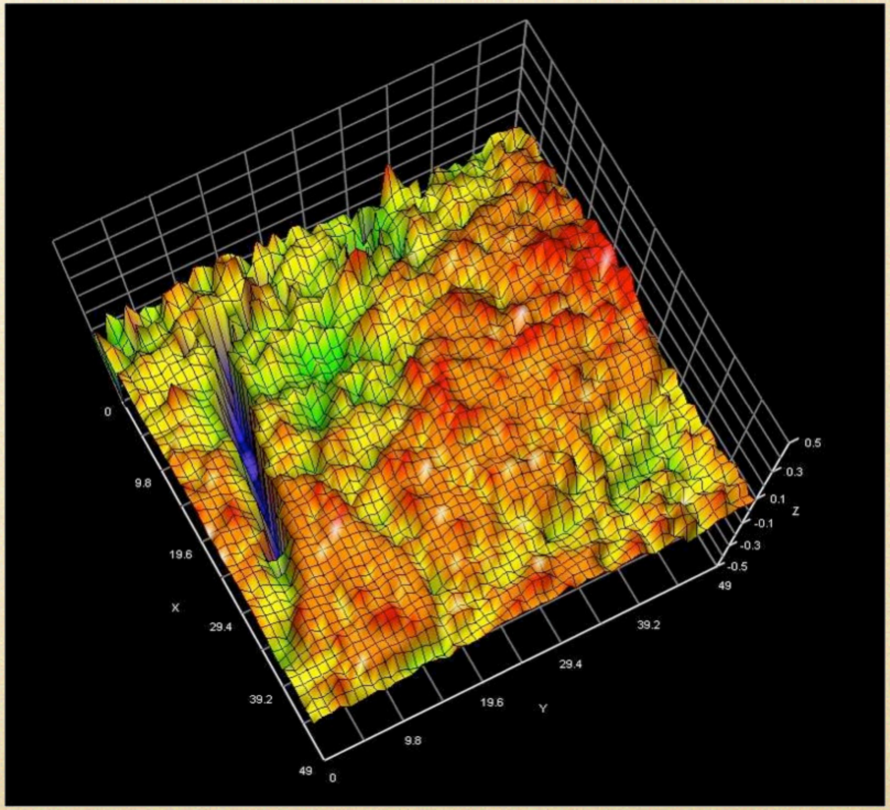
Saleska

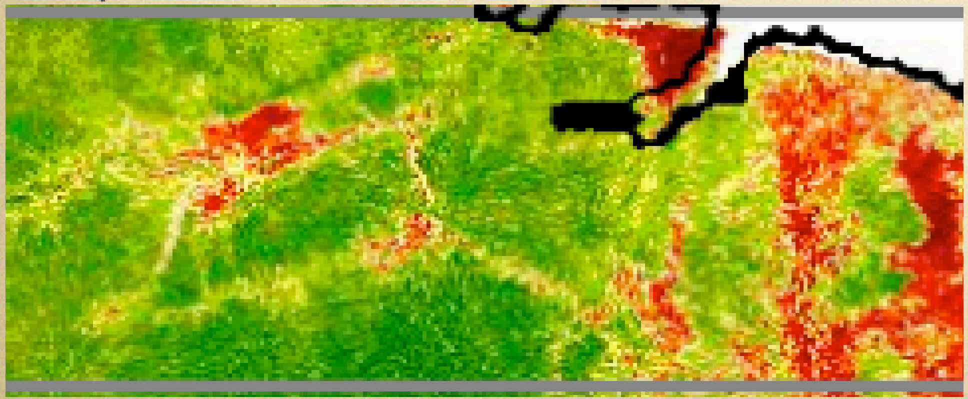
Disturbance at Tapajós

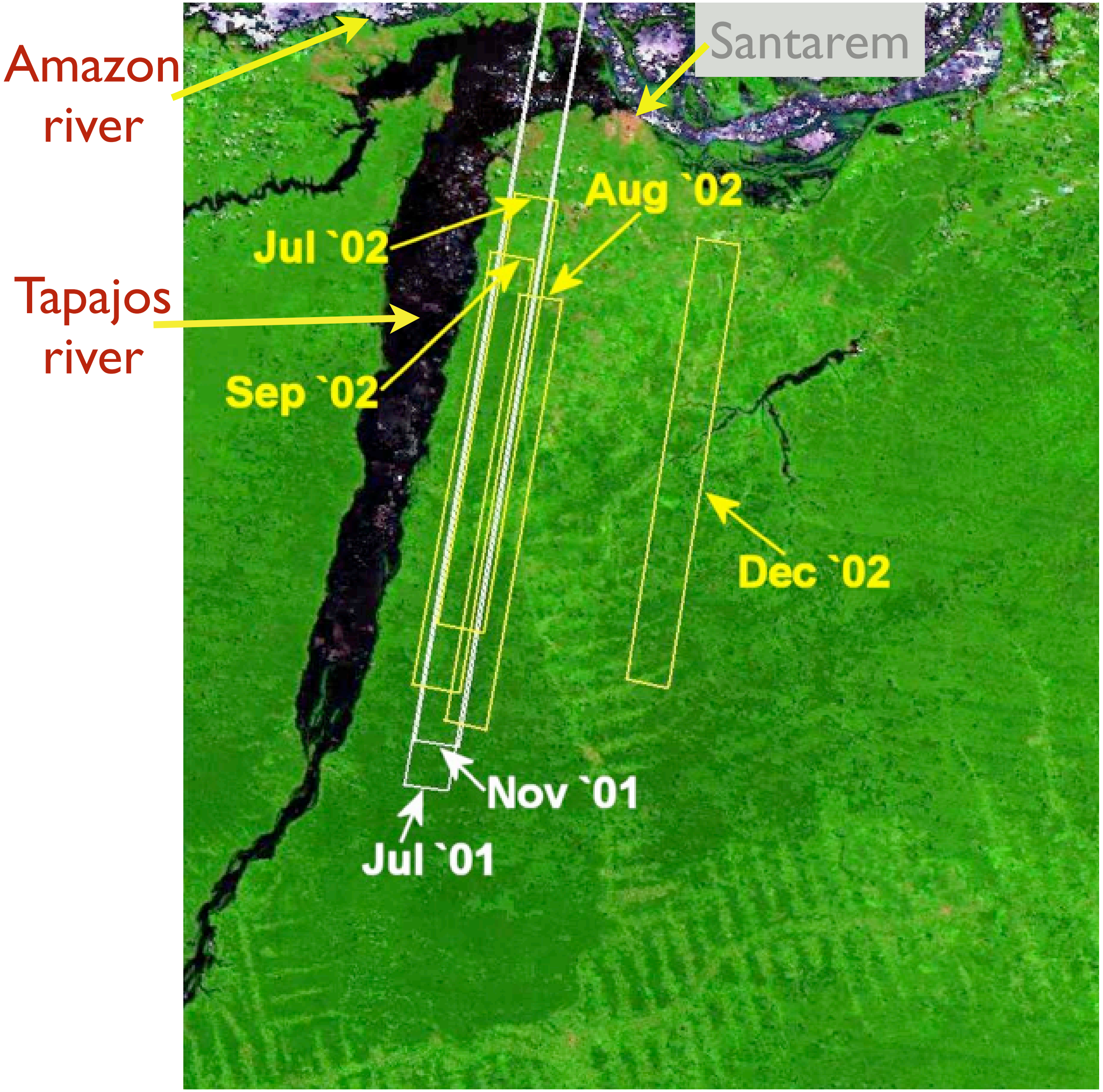
$EVI_{dry-wet}$ (October - June)



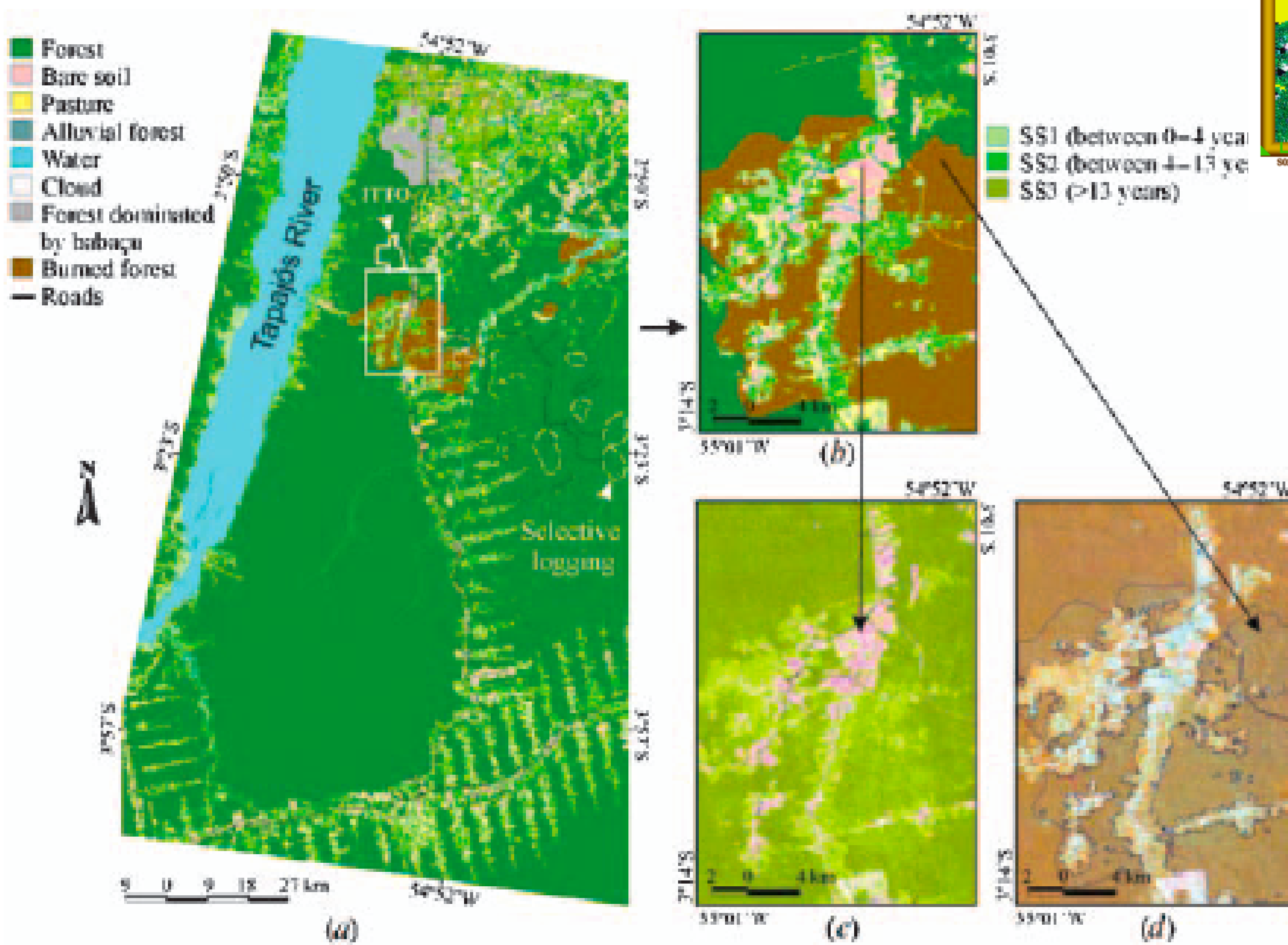
Red colors depict where 'greenning' occurs in the dry season with 'yellows' indicating 'drying'

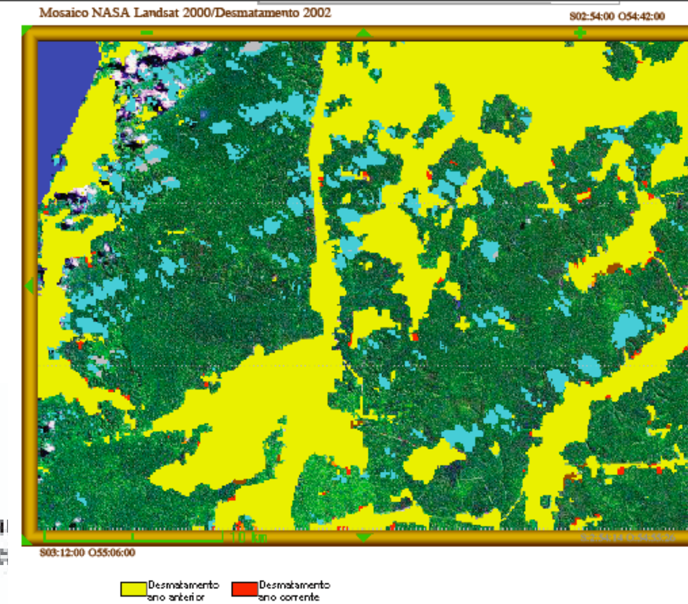






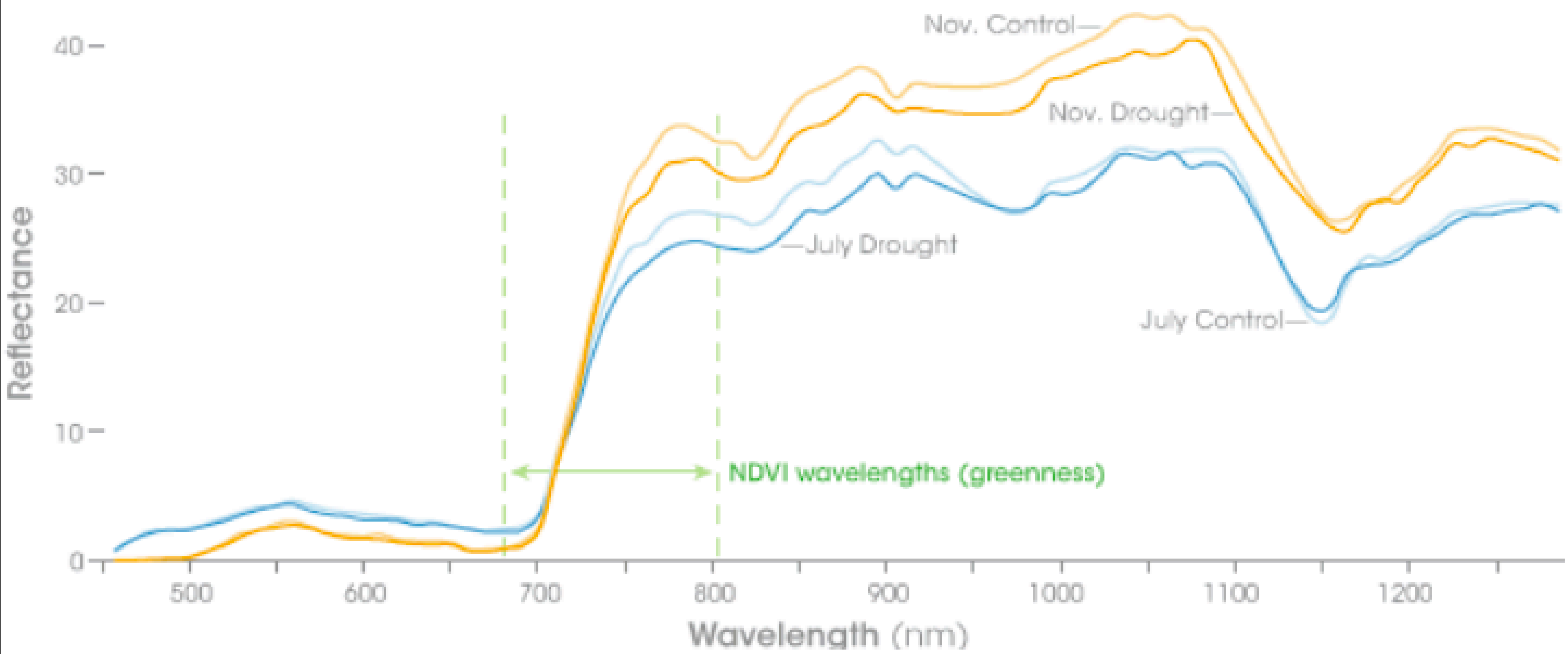
Location of 6 EO-1 Hyperion scene acquisitions within the Floresta Nacional do Tapajós and surrounding areas, south of Santarém in the state of Pará, Brazil; each Hyperion each image is 11km wide.

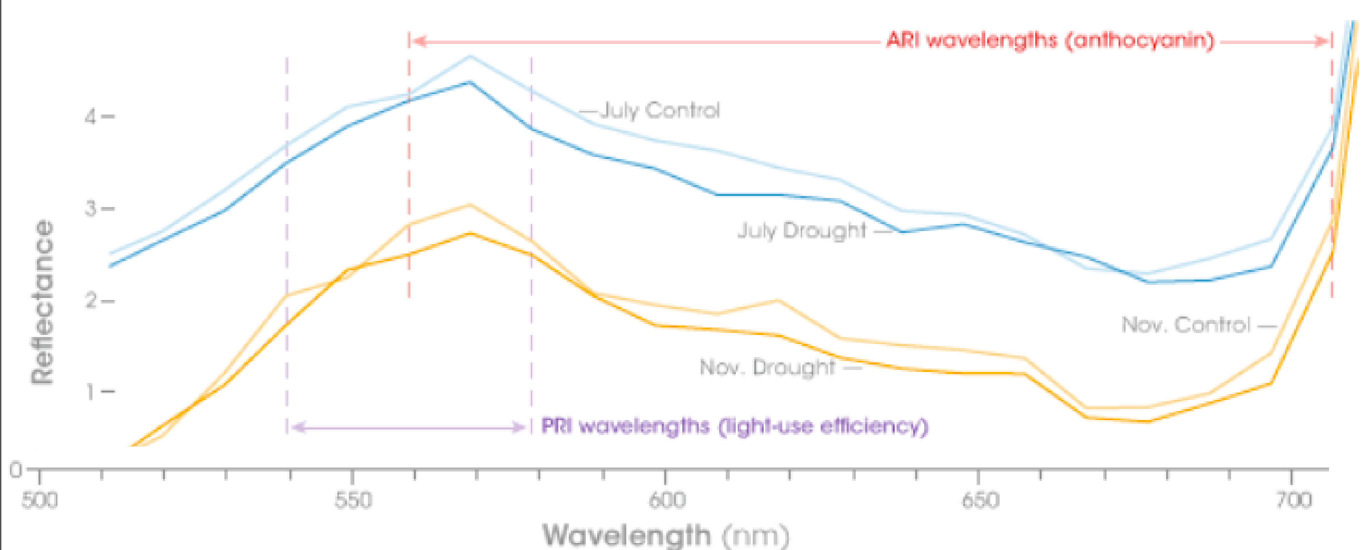




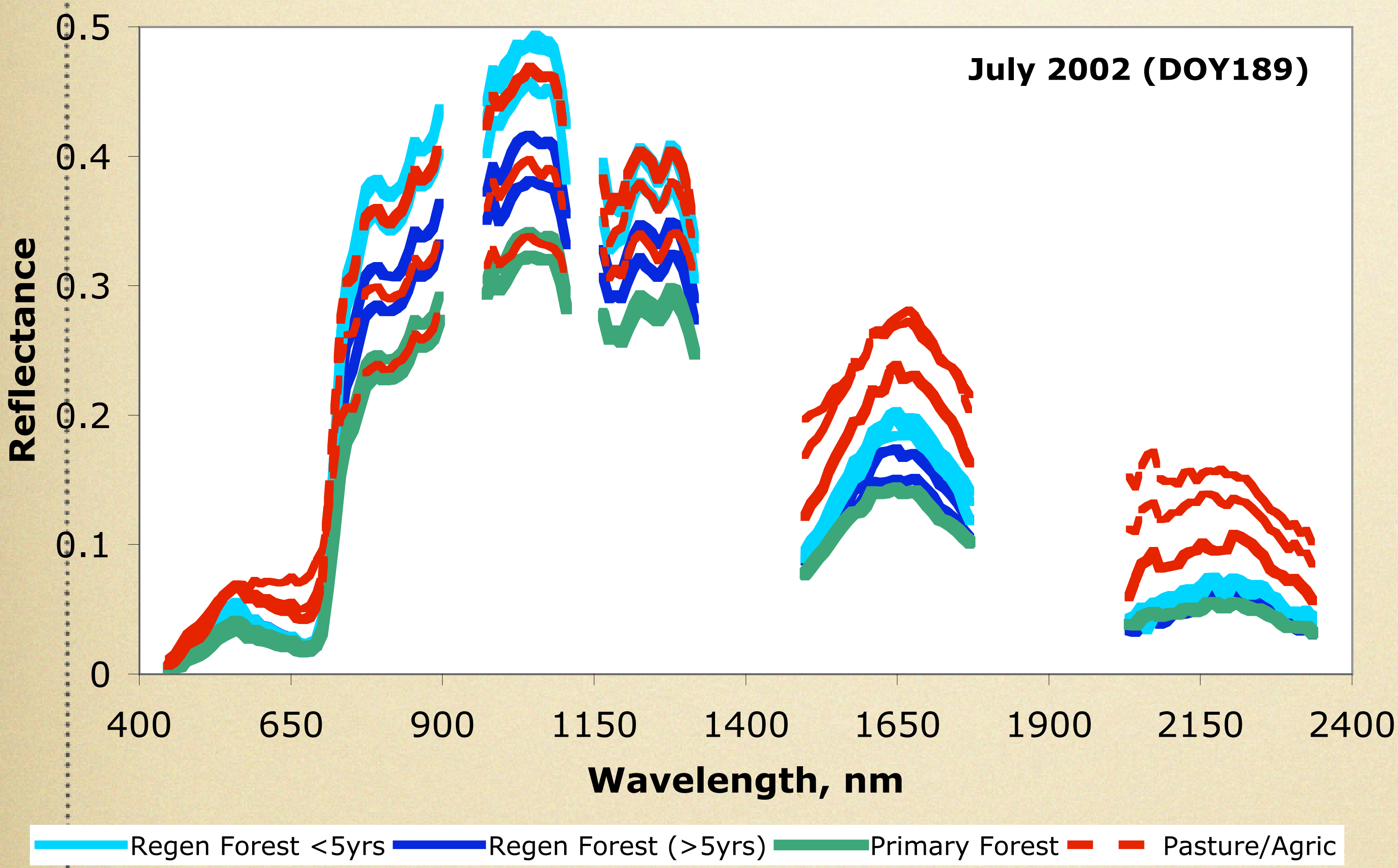
PRODES

Espiritu-Santo et al., 2005 (IJRS)

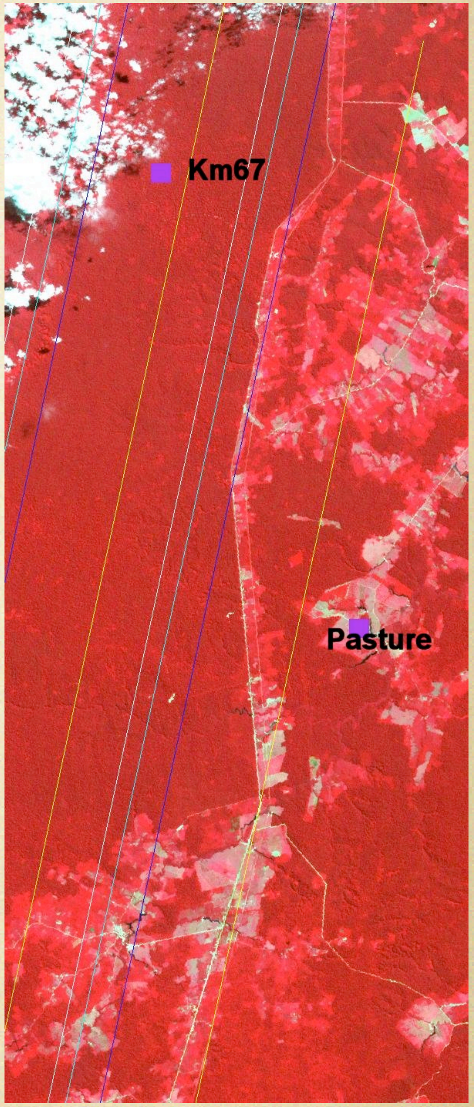




Hyperion data,
Asner

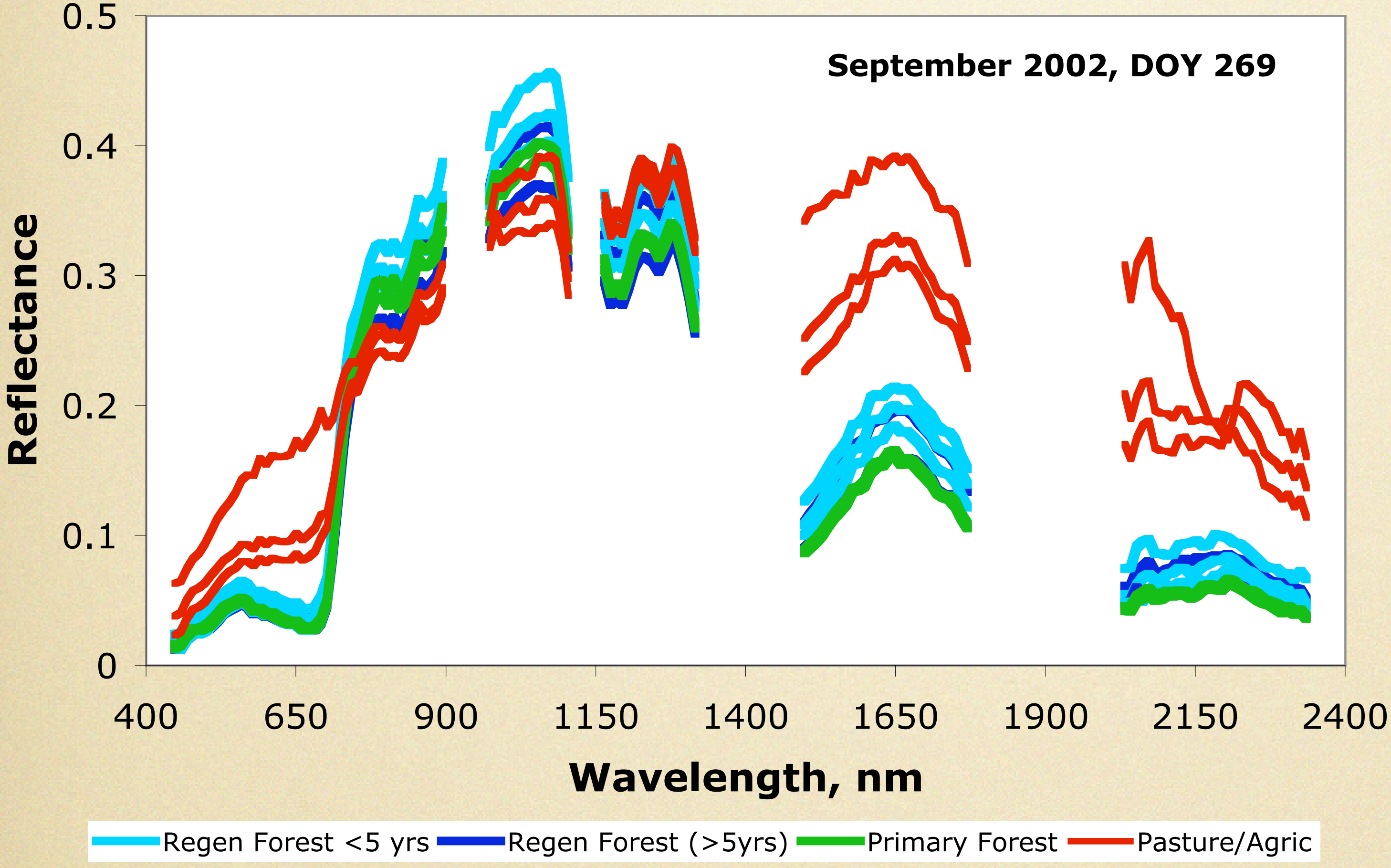


July 2002 (DOY189)
Reflectance
0.5
0.4
0.3
0.2
0.1
0
400
650
900
1150
1400
1650
1900
2150
2400
Wavelength, nm
Regen Forest <5yrs
Regen Forest (>5yrs)
Primary Forest
Pasture/Agric

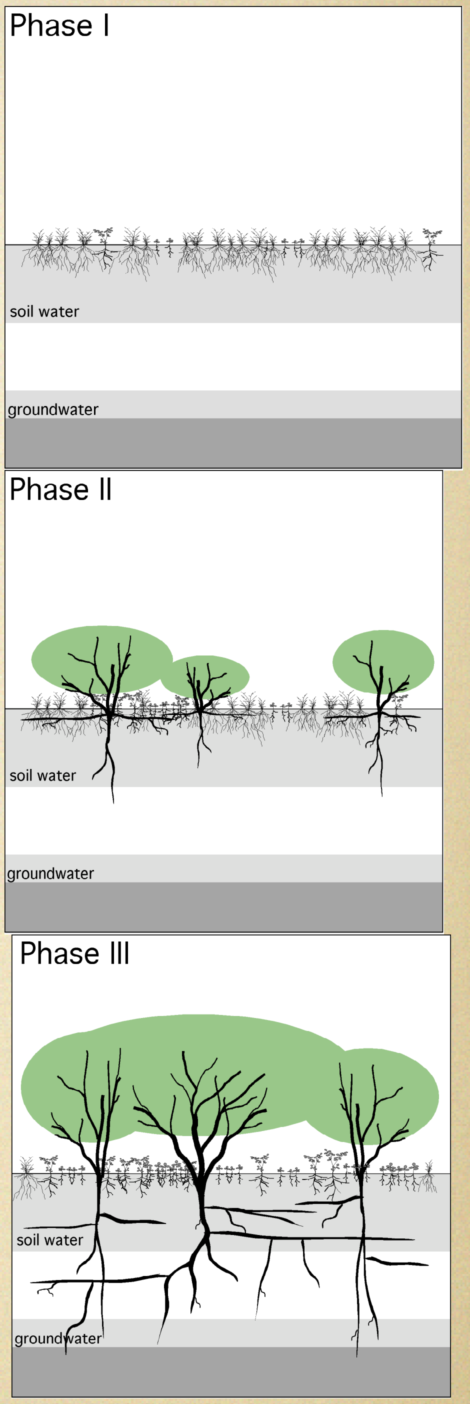


Km67
Pasture

July 2002

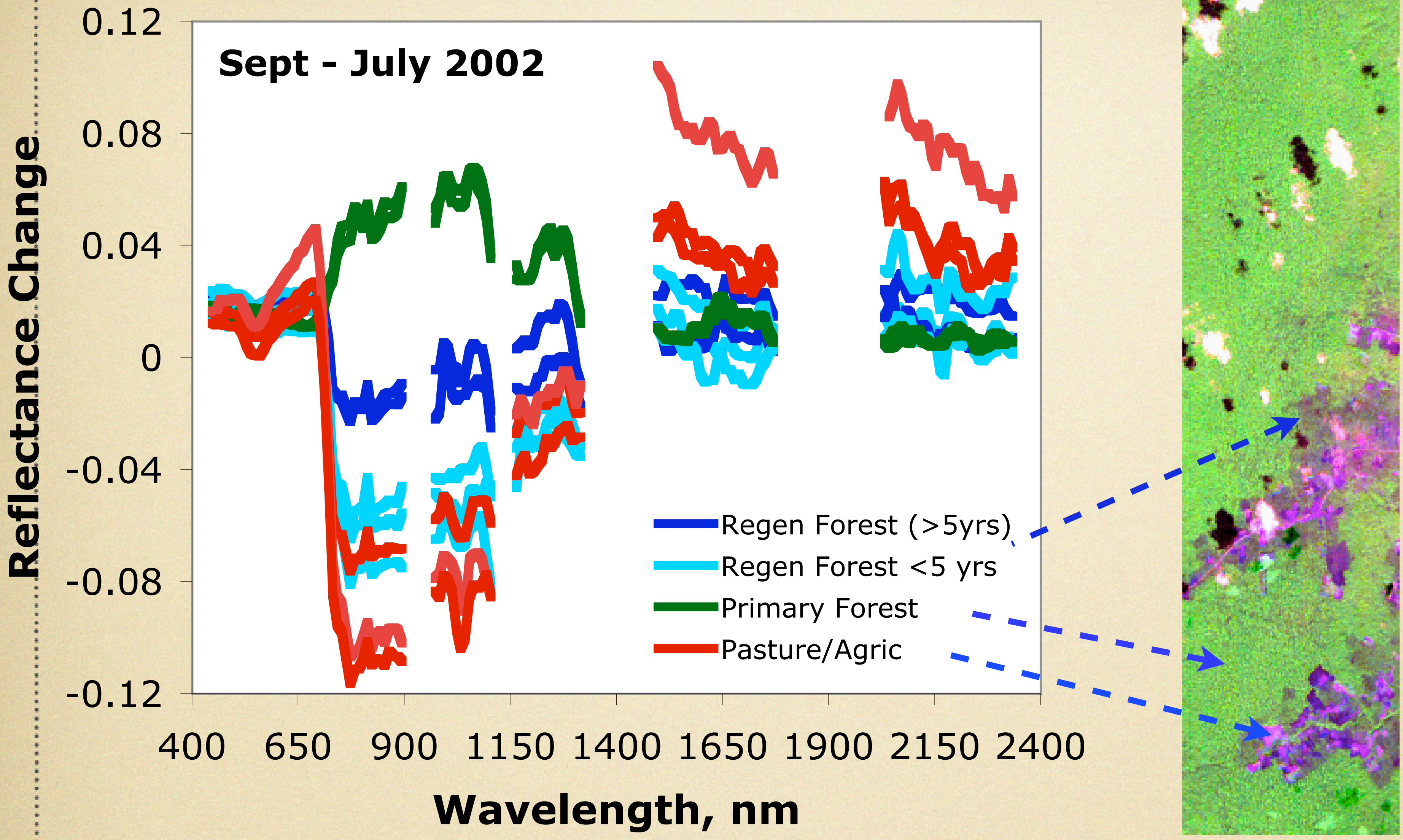


September 2002, DOY 269
Reflectance
0
0.1
0.2
0.3
0.4
0.5
Wavelength, nm
400
650
900
1150
1400
1650
1900
2150
2400
Regen Forest <5 yrs
Regen Forest (>5yrs)
Primary Forest
Pasture/Agric



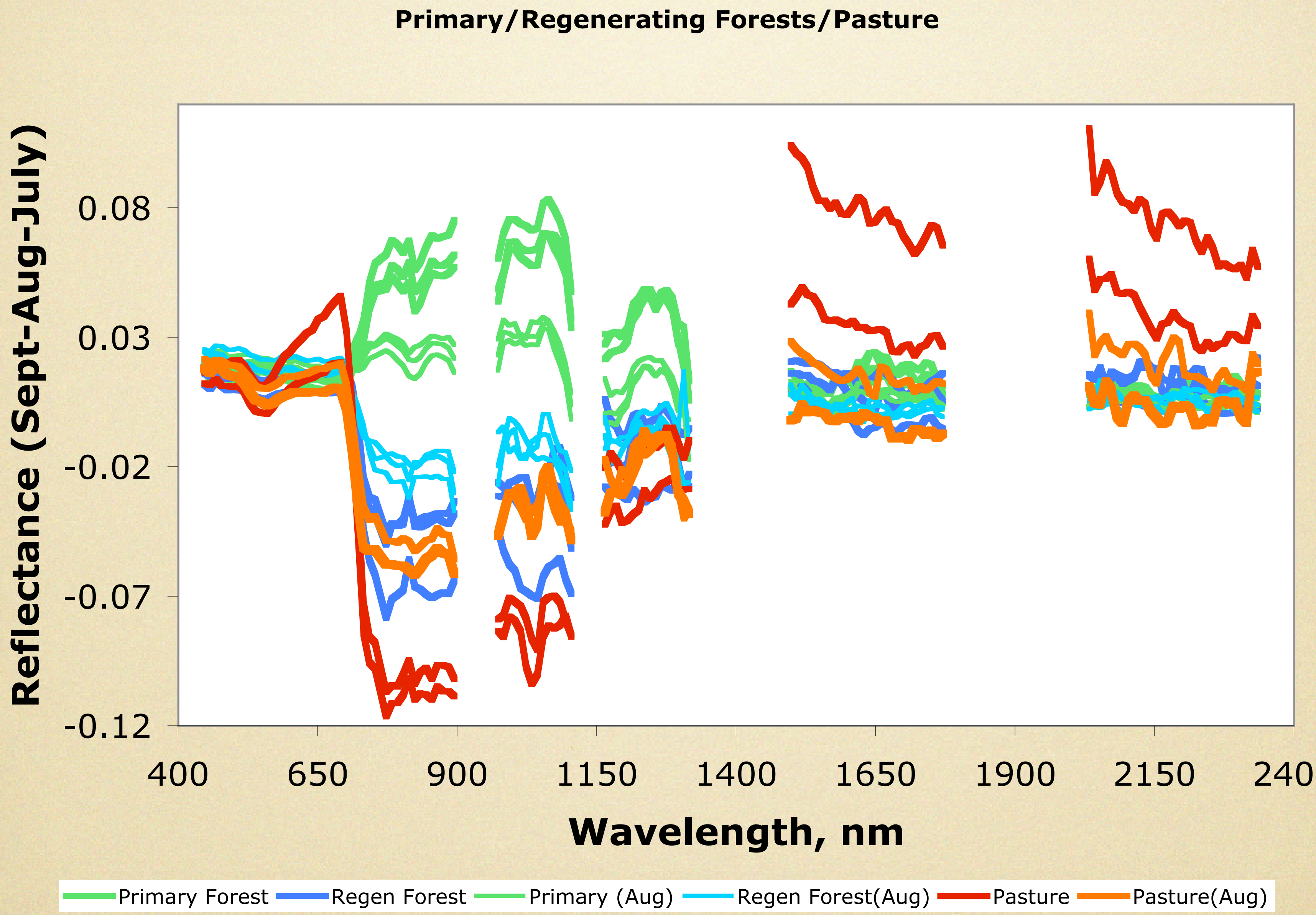
Phase I
soil water
groundwater
Phase II
soil water
groundwater
Phase III
soil water
groundwater

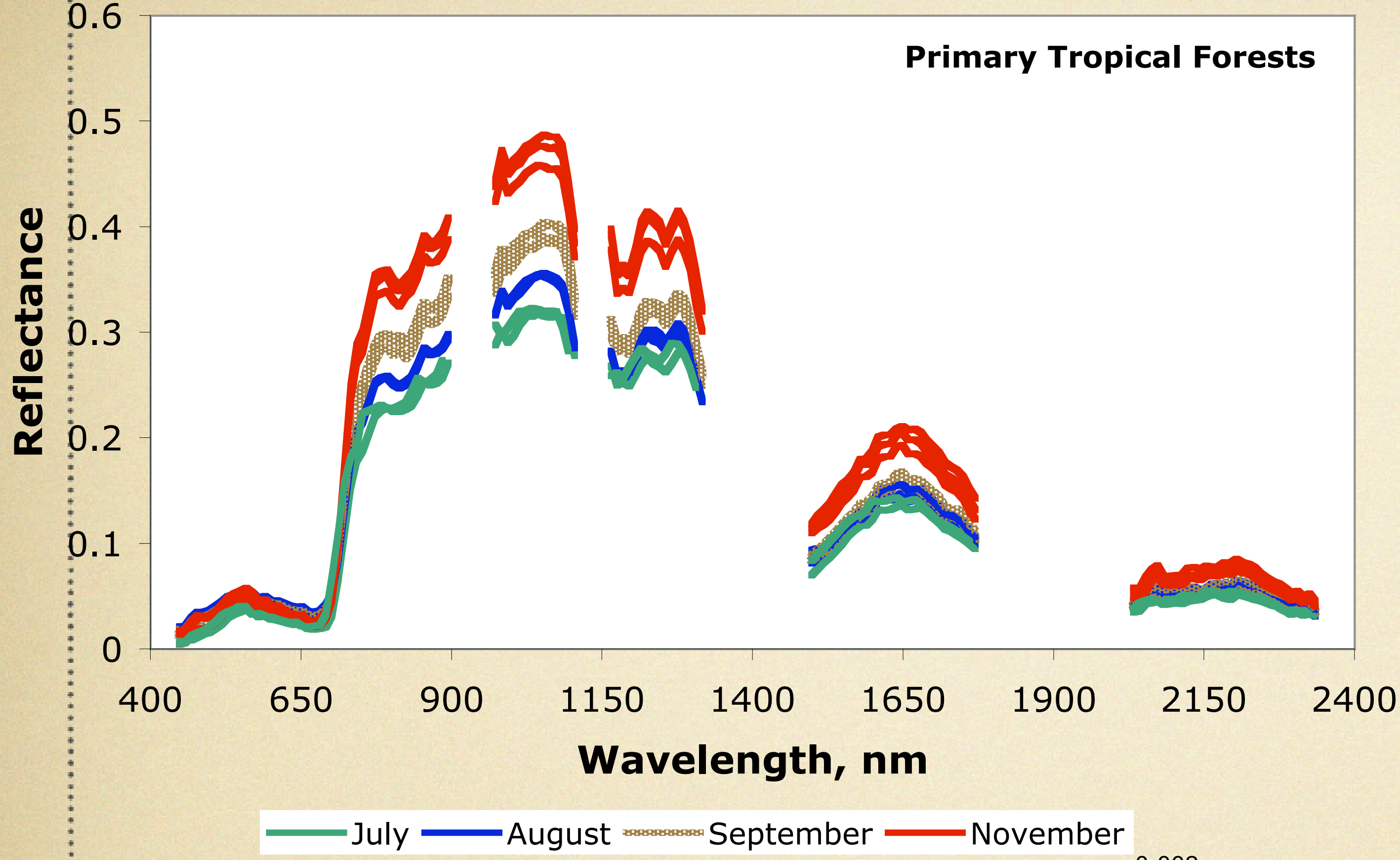
Reflectance Difference



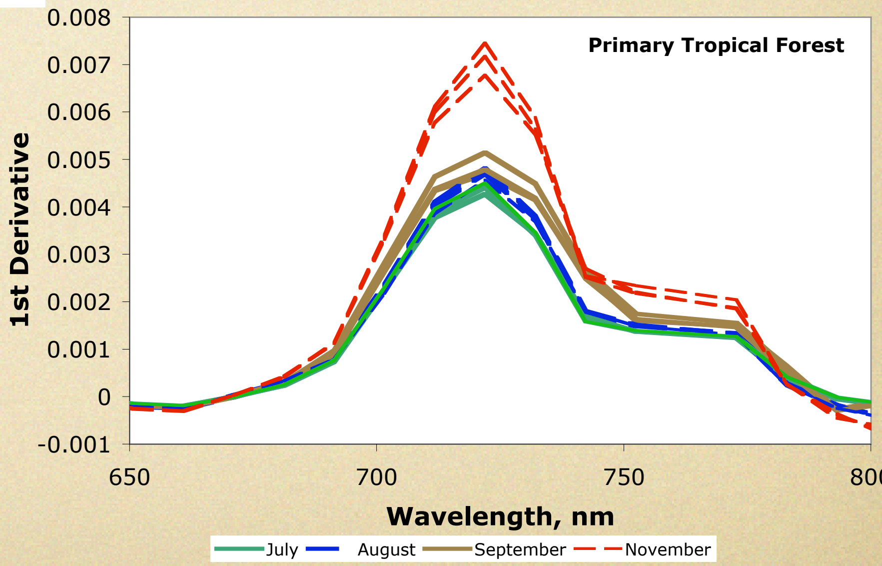
Red (640nm), NIR (854nm), SWIR (2133 nm) composite ‘reflectance change’ image with green denoting positive NIR change; pink and brown colors are negative NIR and positive red & SWIR changes.

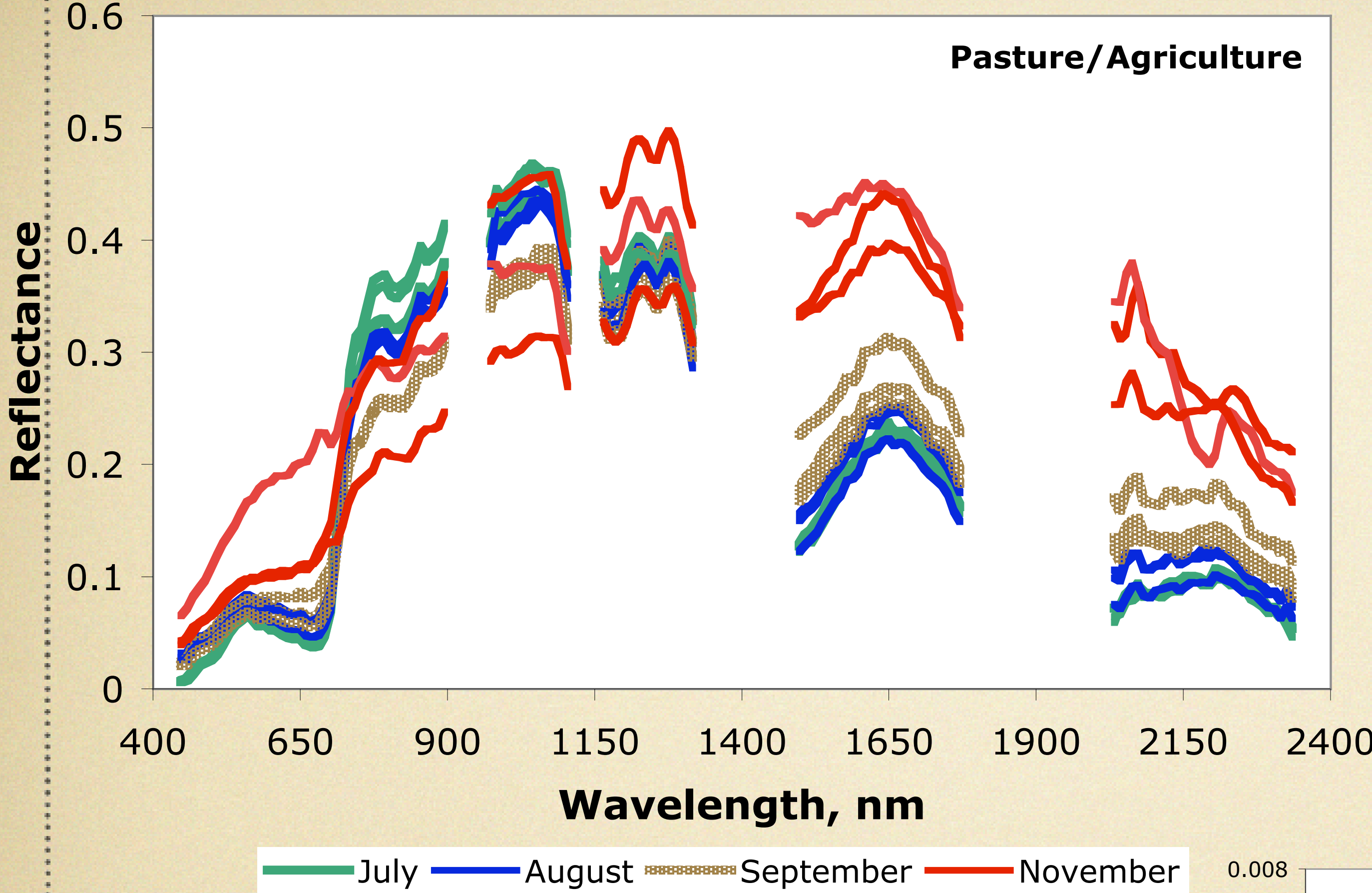
Reflectance Differences (Jul-Aug-Sep)



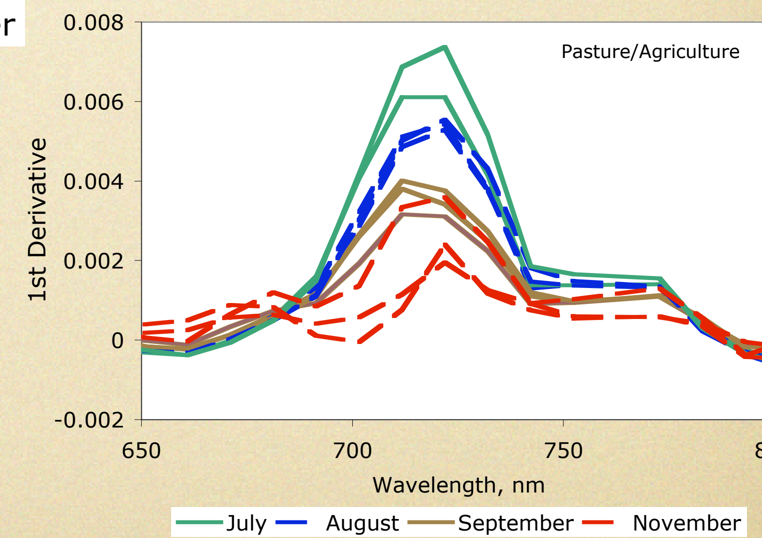


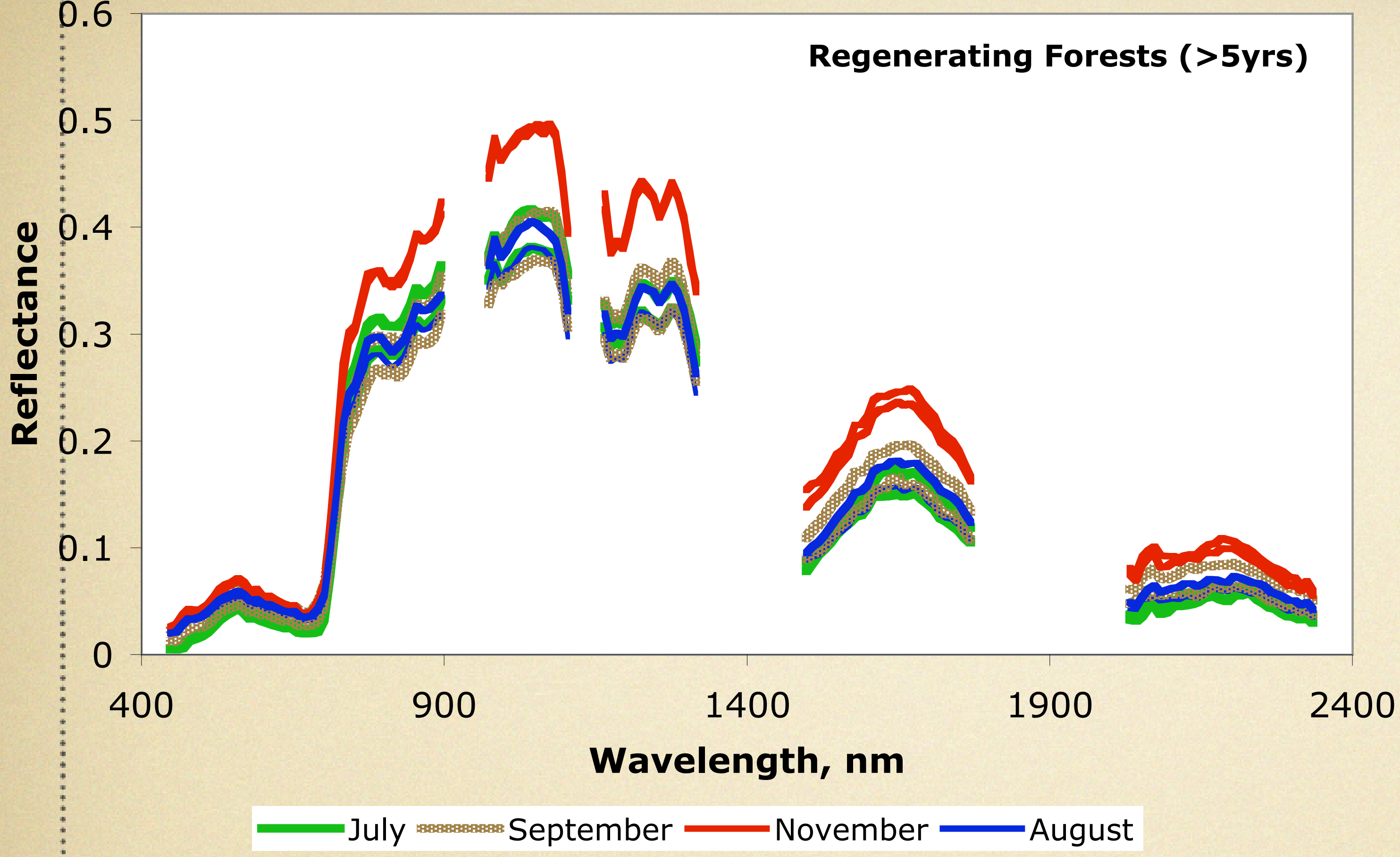
Hyperion-measured seasonal sequence of primary forests

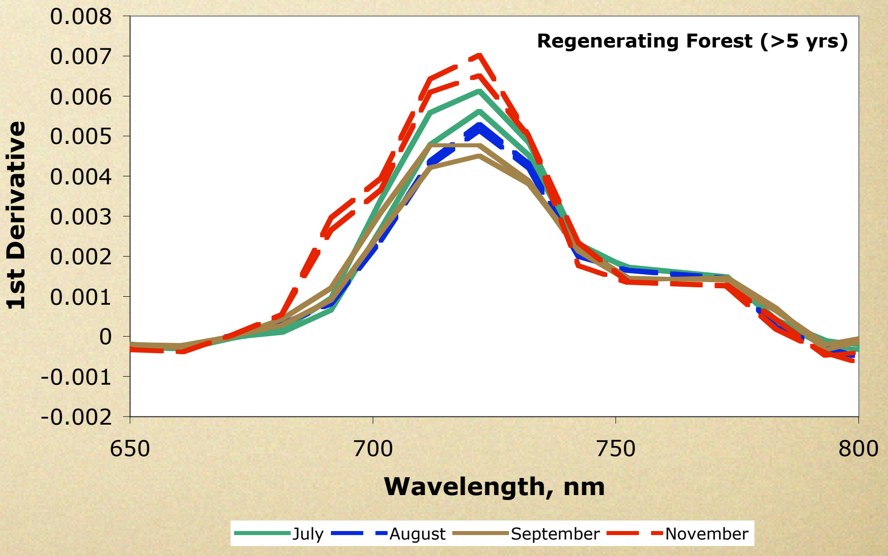




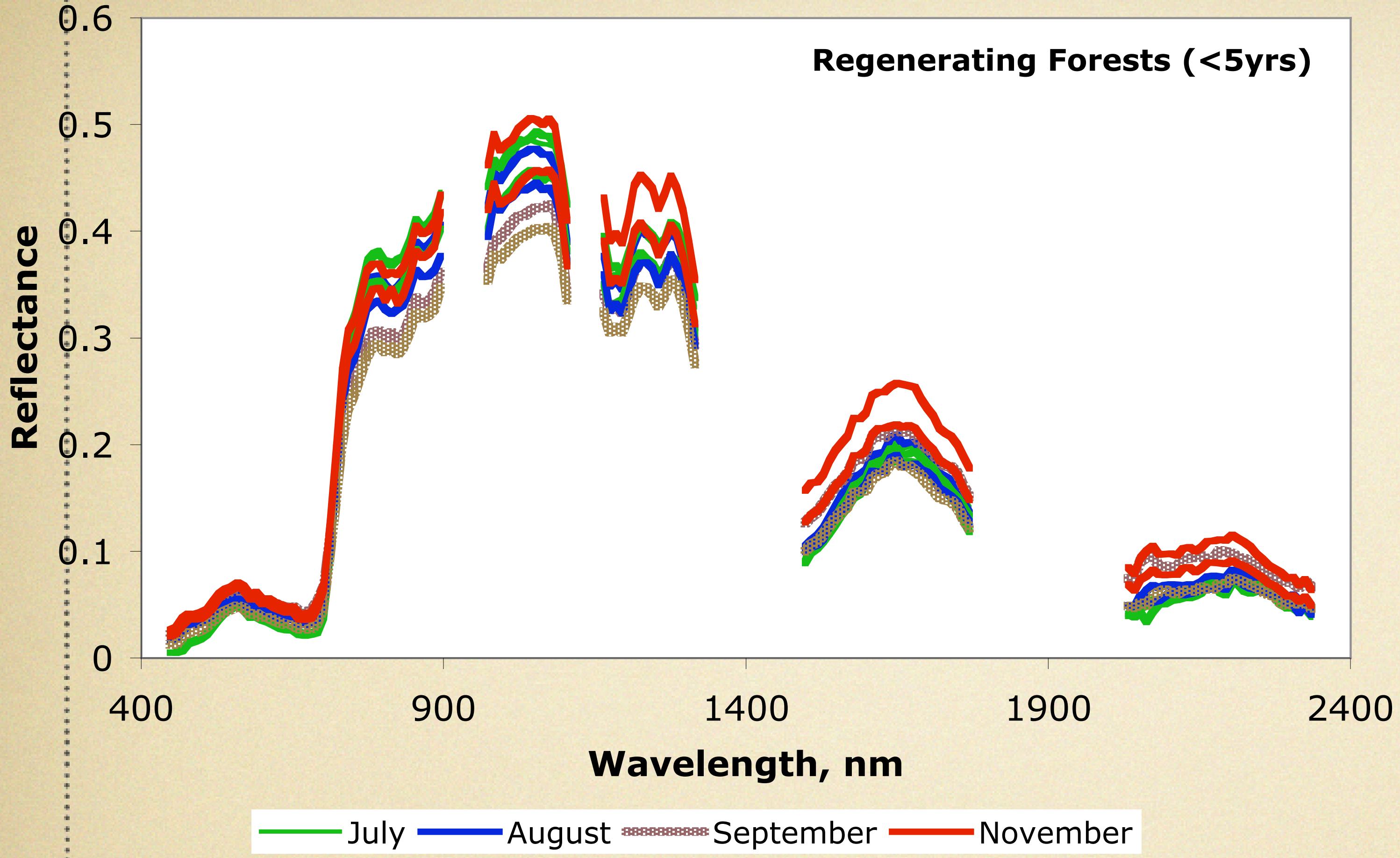
Hyperion-measured seasonal sequence of pasture/ agriculture



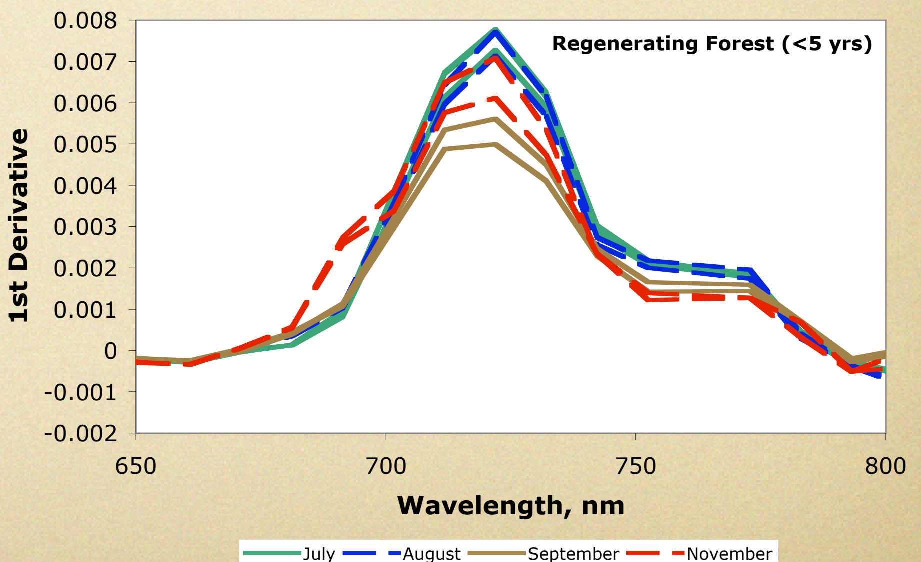




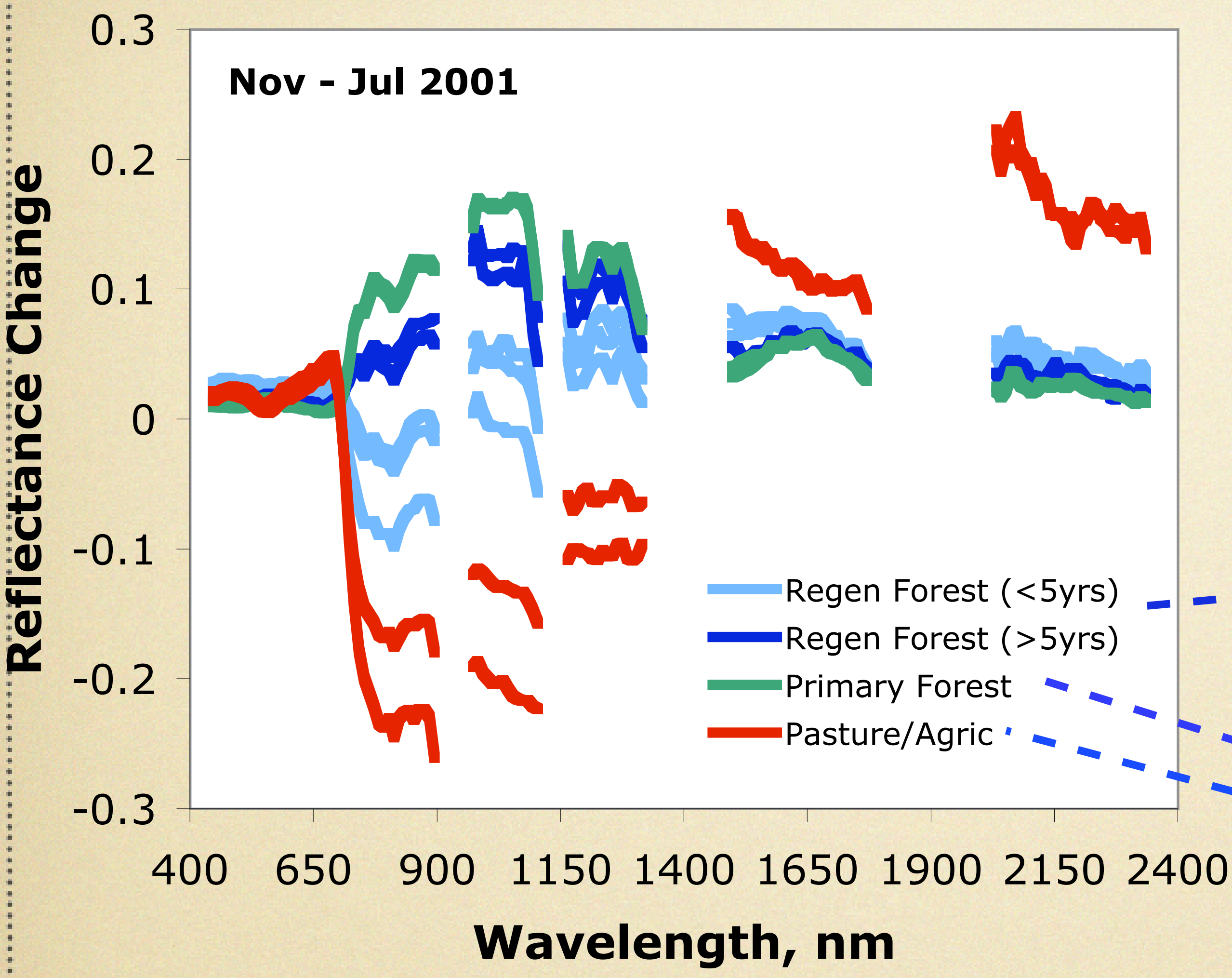
Hyperion-measured seasonal sequence of regenerating forests (>5 yrs)

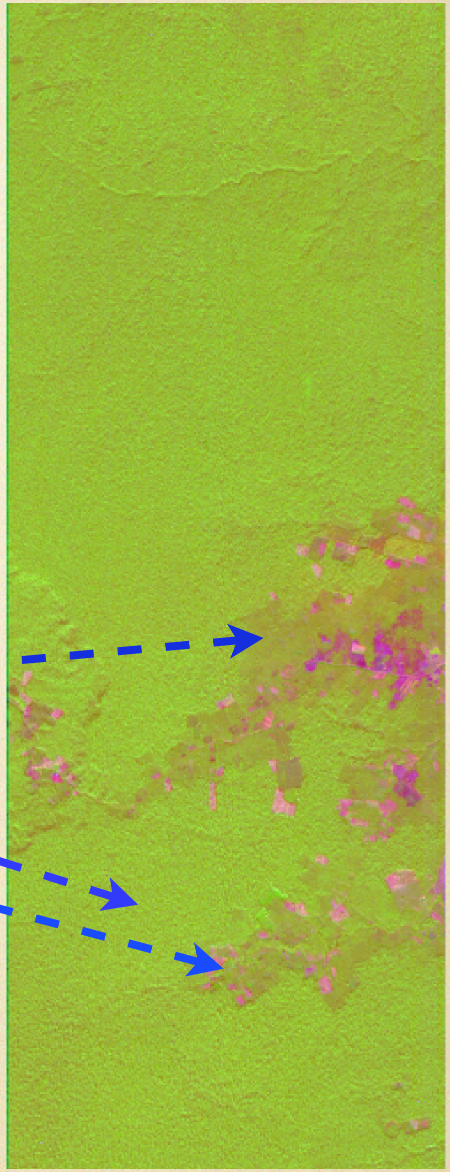


Hyperion-measured seasonal sequence of regenerating forests (<5 yrs)



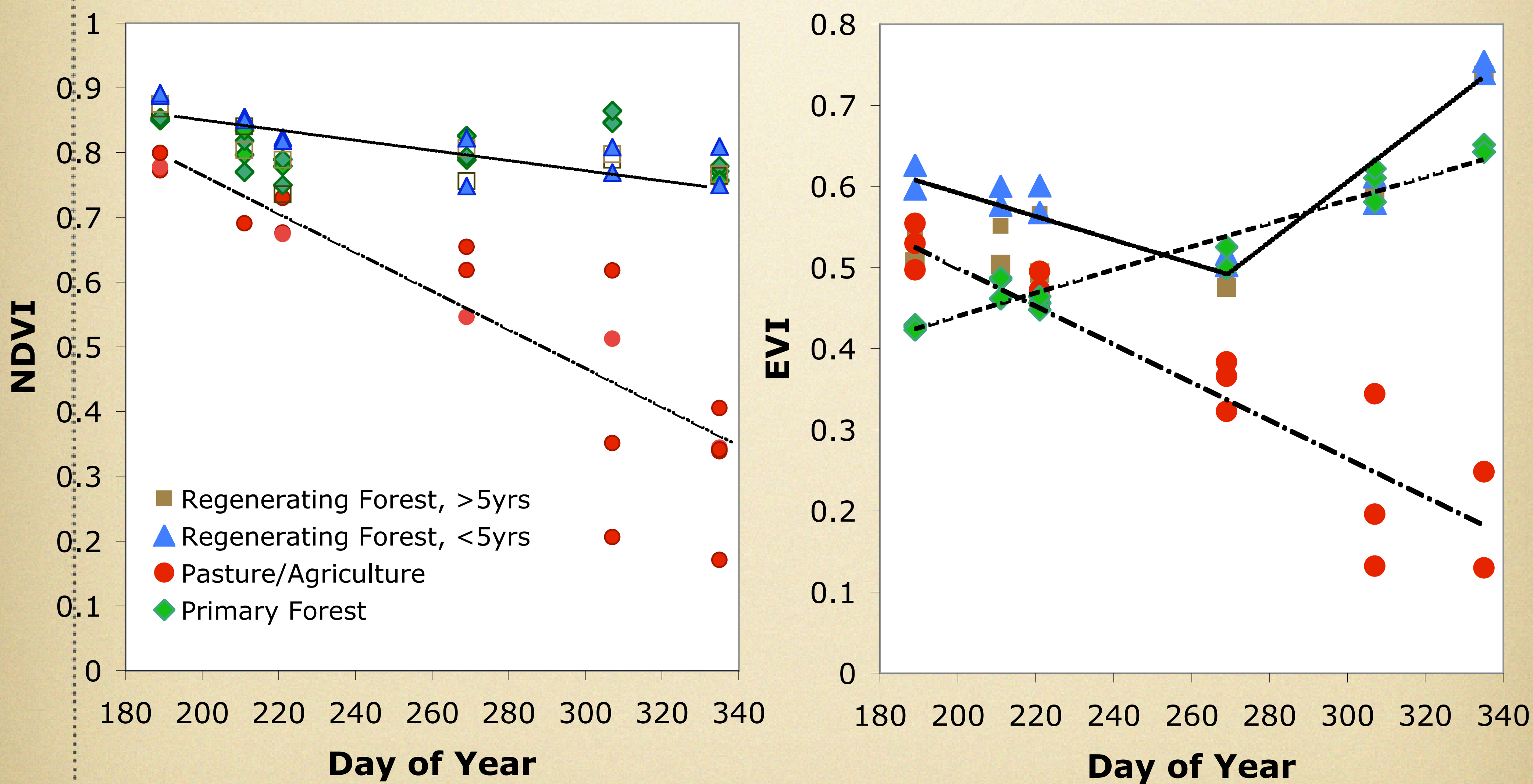
2001 Reflectance Difference



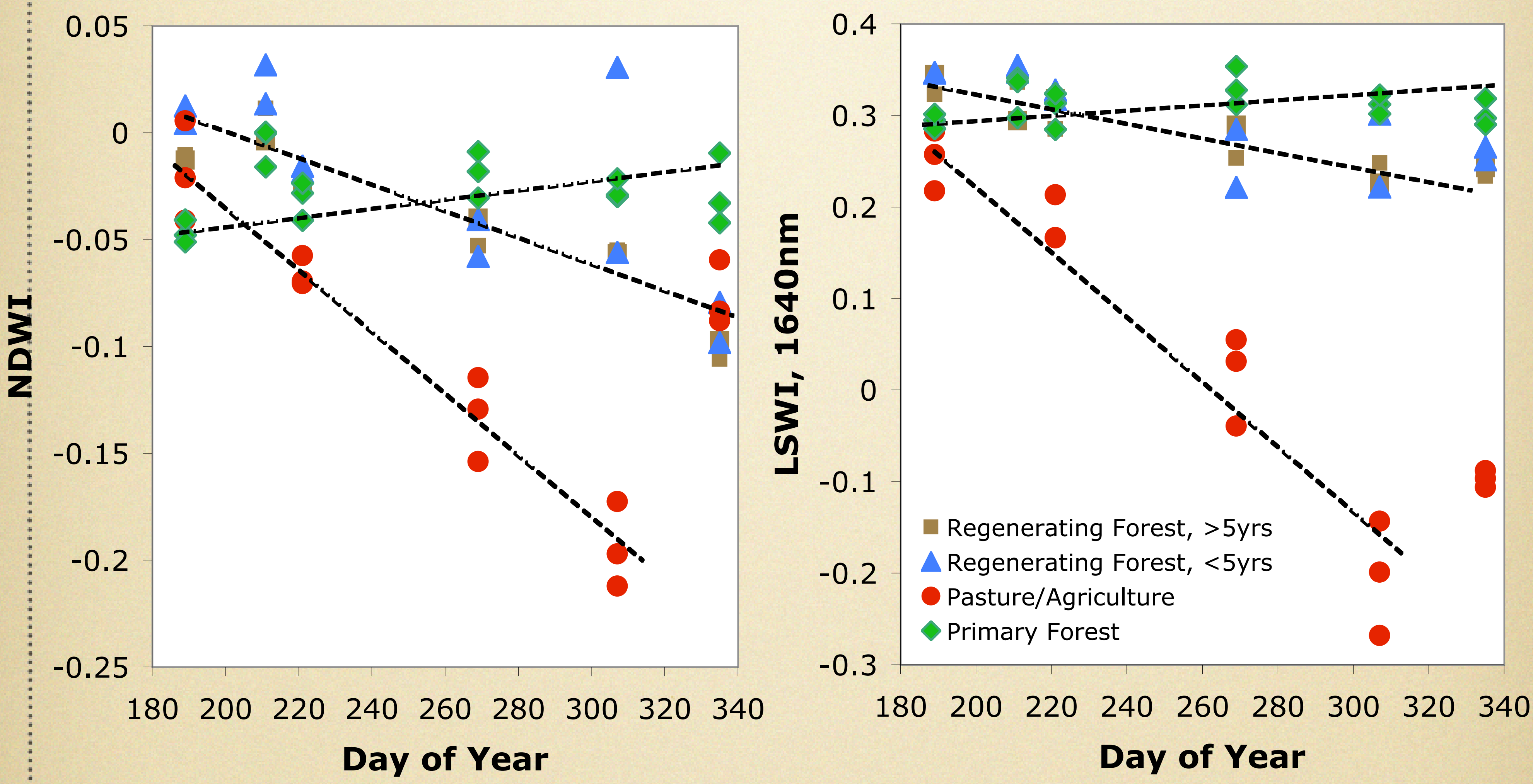


Red (640nm), NIR (854nm), SWIR (2133 nm) composite 'reflectance change' image with green denoting positive NIR change; pink and brown colors are negative NIR and positive red & SWIR changes.

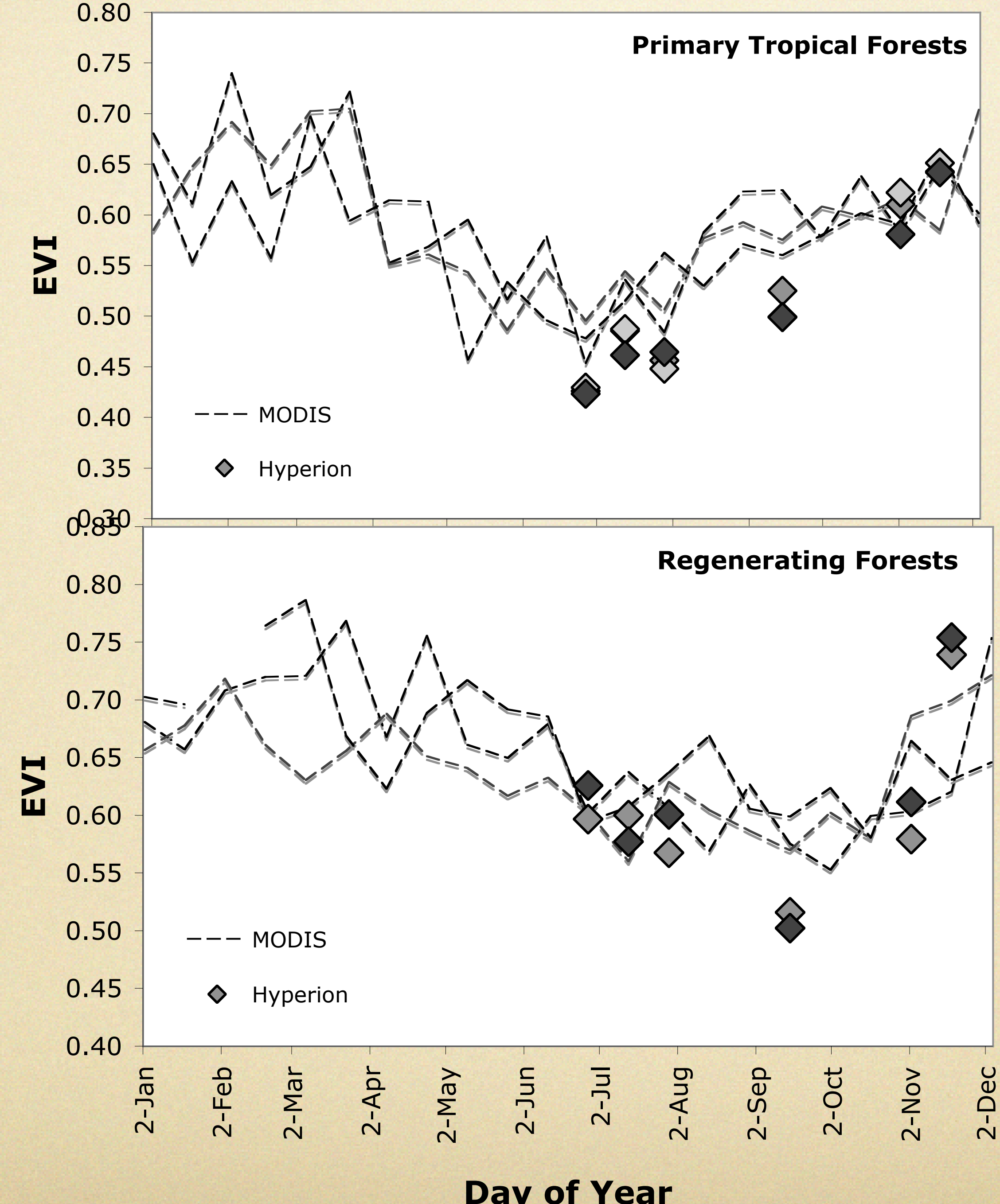
Dry season phenology profiles depicted by NDVI and EVI



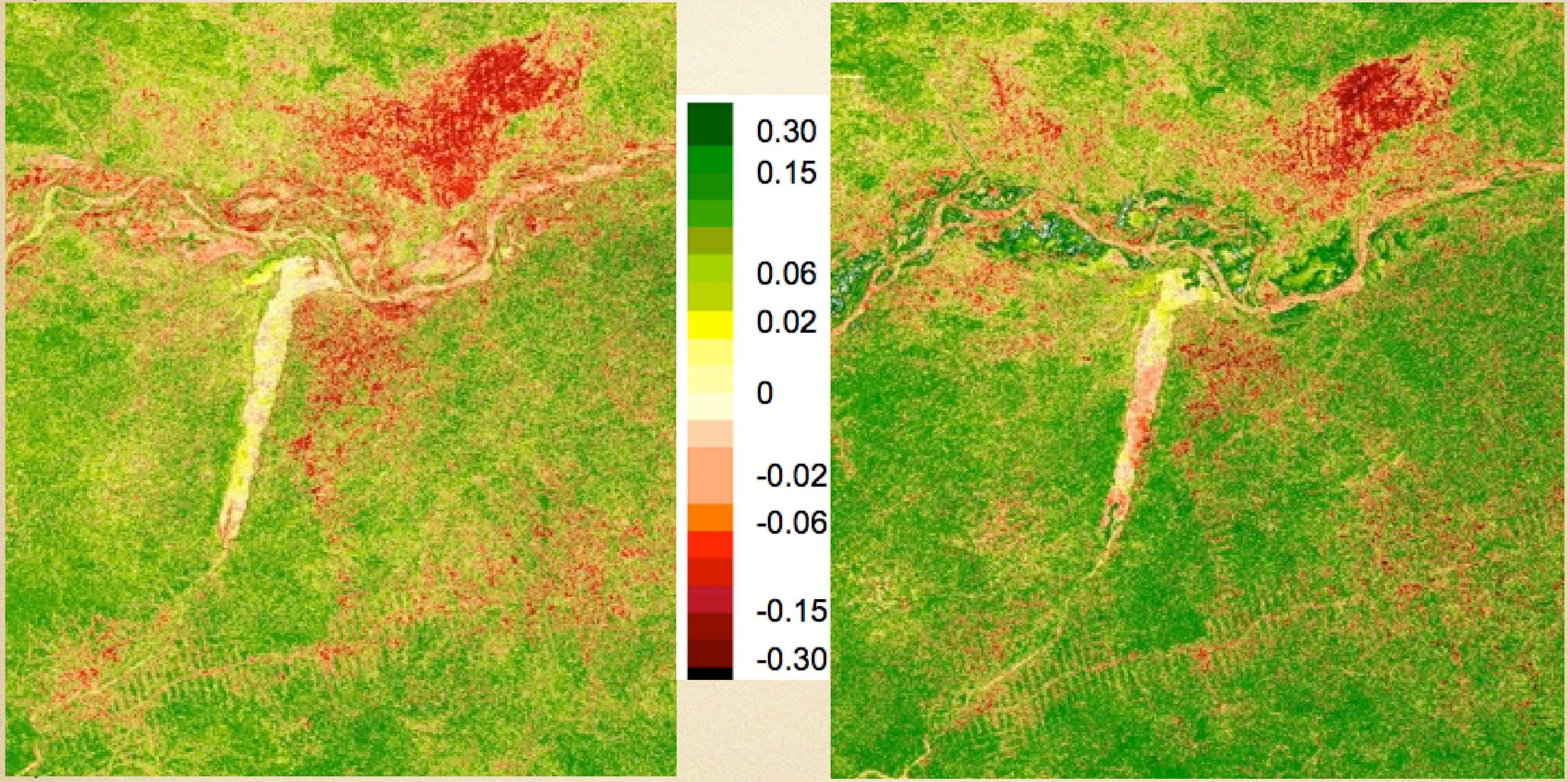
Dry season phenology profiles depicted by NDWI and LSWI



Hyperion dry season phenology profiles plotted with annual MODIS 250m EVI observations



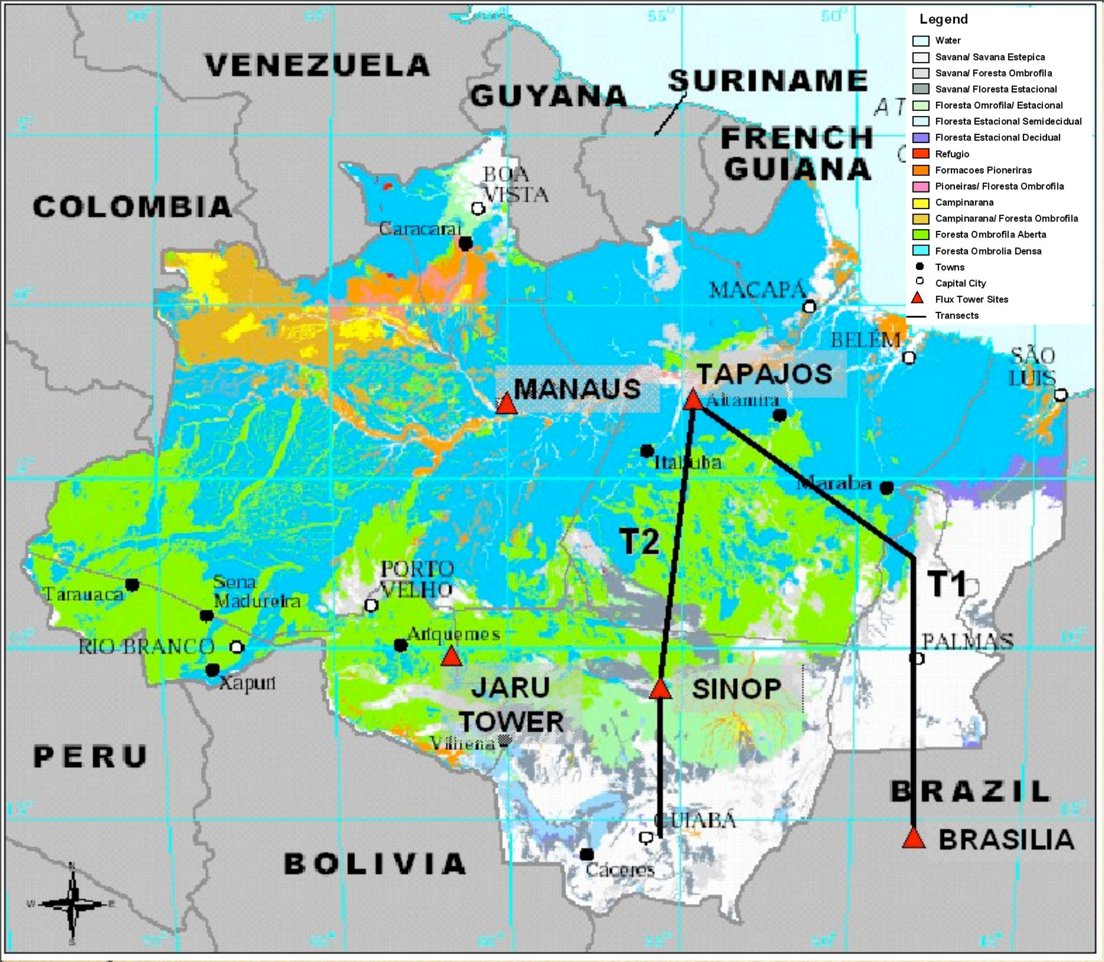
MODIS 250m EVI difference image



Sept - Jul

Nov - Jul

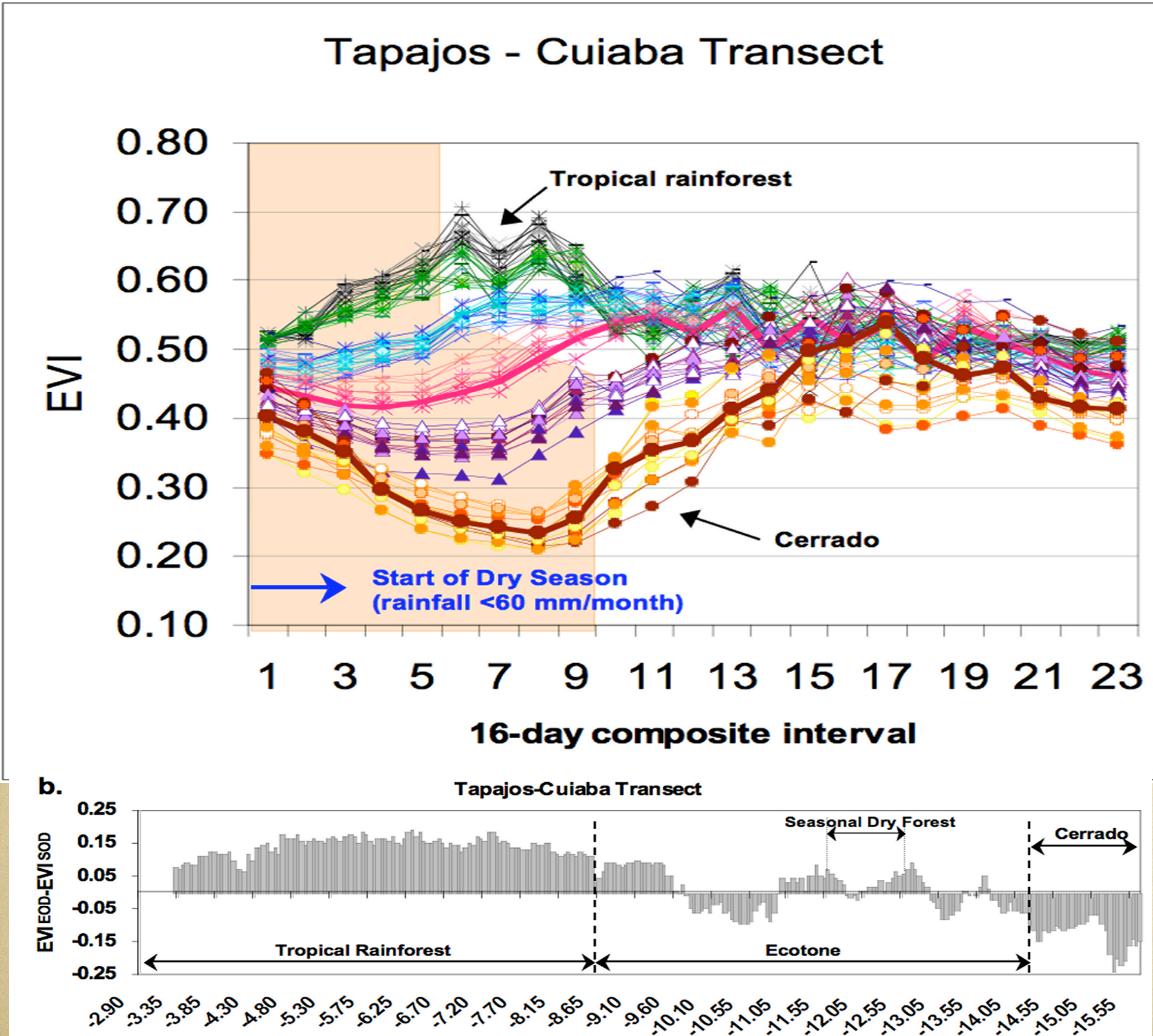
Red colors indicate negative EVI trends and green colors depict positive EVI trends in the dry season.



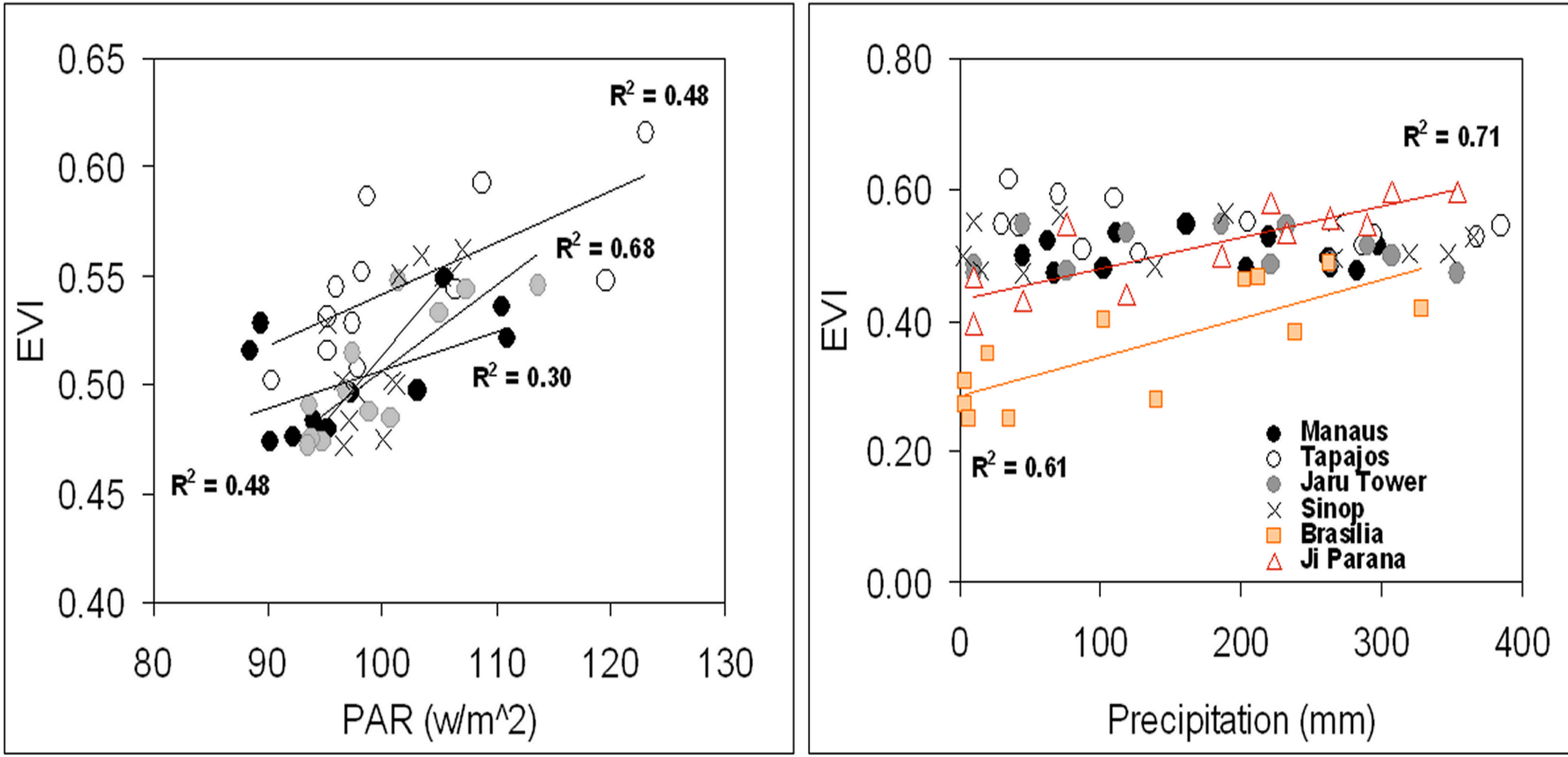
Ecotone Rainforests (Transitional)

- Both light and moisture controls on ecosystem metabolism and productivity

Ratana, P

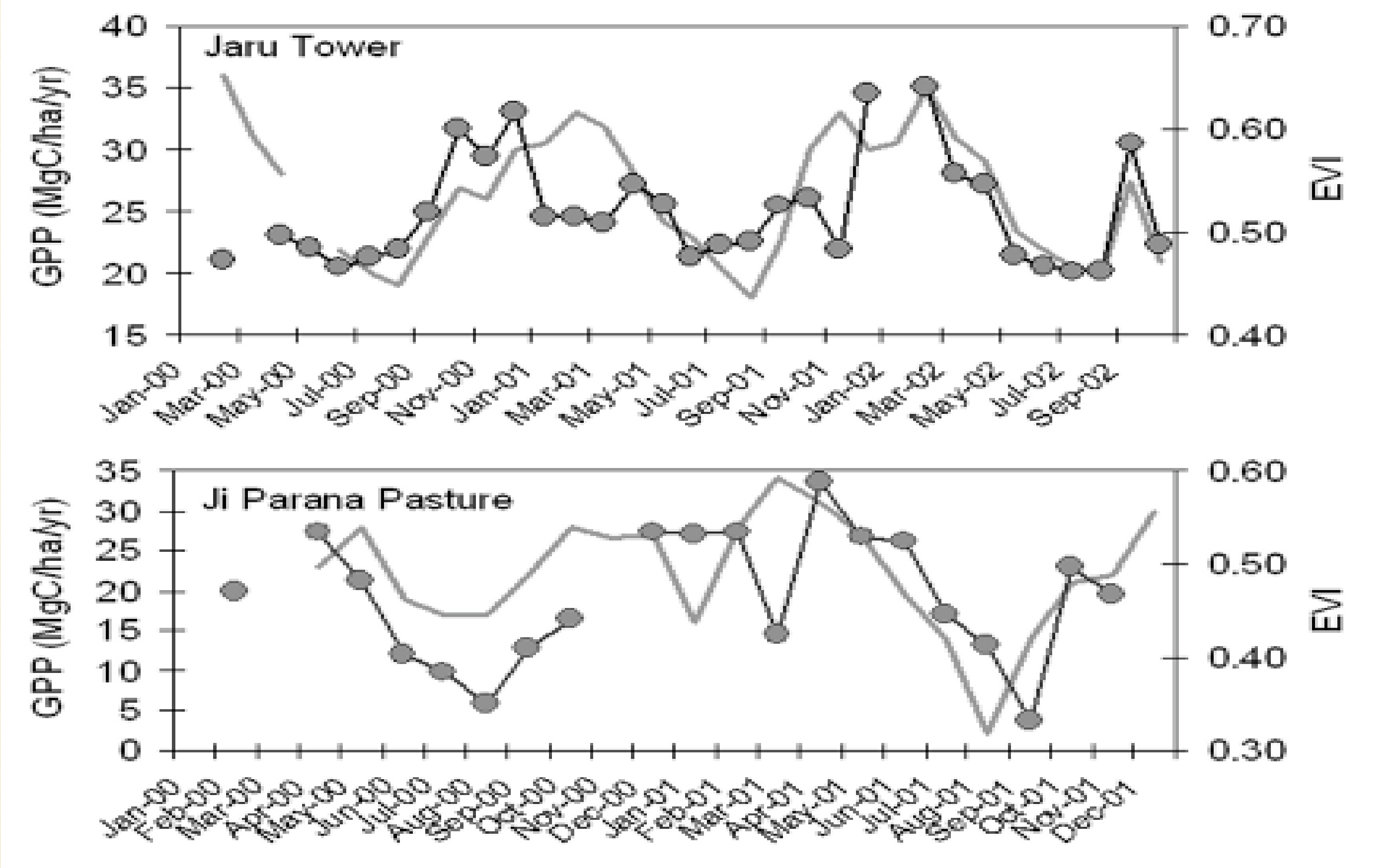

Tapajos - Cuiaba Transect
EVI
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
Tropical rainforest
Cerrado
Start of Dry Season
(rainfall <60 mm/month)
1 3 5 7 9 11 13 15 17 19 21 23
16-day composite interval
b.
Tapajos-Cuiaba Transect
EVI EOD-EVI SOD
0.25
0.15
0.05
-0.05
-0.15
-0.25
Seasonal Dry Forest
Cerrado
Tropical Rainforest
Ecotone
-2.90 -3.35 -3.85 -4.30 -4.80 -5.30 -5.75 -6.25 -6.70 -7.20 -7.70 -8.15 -8.65 -9.10 -9.60 -10.10 -10.55 -11.05 -11.55 -12.05 -12.55 -13.05 -13.55 -14.05 -14.55 -15.05 -15.55

Ratana, P



0.65
0.60
0.55
0.50
0.45
0.40
EVI
80
90
100
110
120
130
PAR (w/m^2)
R2 = 0.48
R2 = 0.68
R2 = 0.30
R2 = 0.48
0.80
0.60
0.40
0.20
0.00
EVI
0
100
200
300
400
Precipitation (mm)
R2 = 0.71
R2 = 0.61
Manaus
Tapajos
Jaru Tower
Sinop
Brasilia
Ji Parana

Consistency with Flux Tower Data



Conclusions

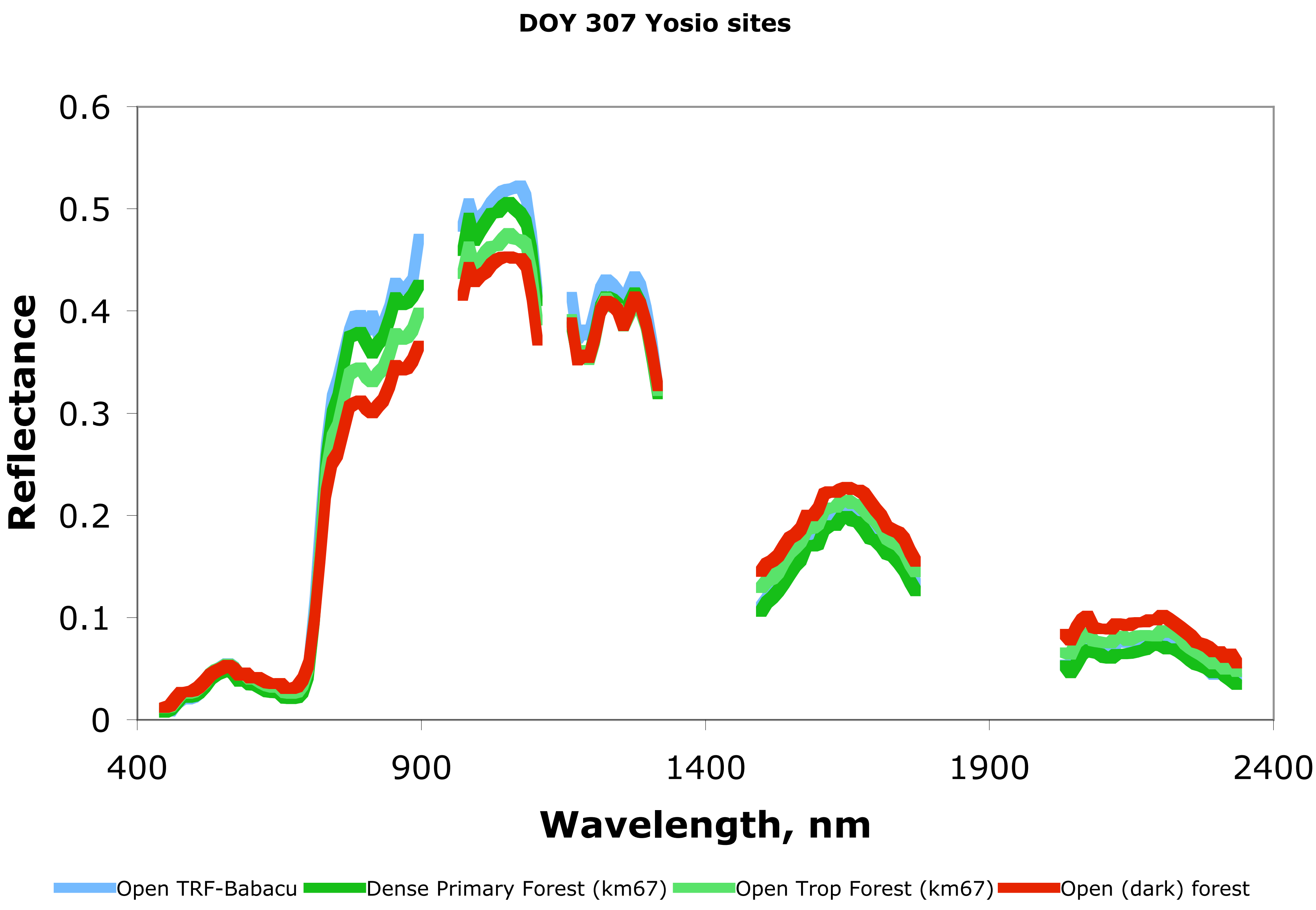
- Satellite phenological observations and tower flux measurements represent important site-specific and community-level responses to environmental variation and change.
- The Hyperion data provided information of land cover characteristics that helped explain the coarser temporal patterns observed with MODIS.
- We found gradients of moisture and light controls across the ecotone as well as distinct phenology shifts associated with disturbance and land use history.
- Flux tower measurements were consistent with the satellite data providing opportunities for aggregation and scaling of the in-situ with satellite measurements.

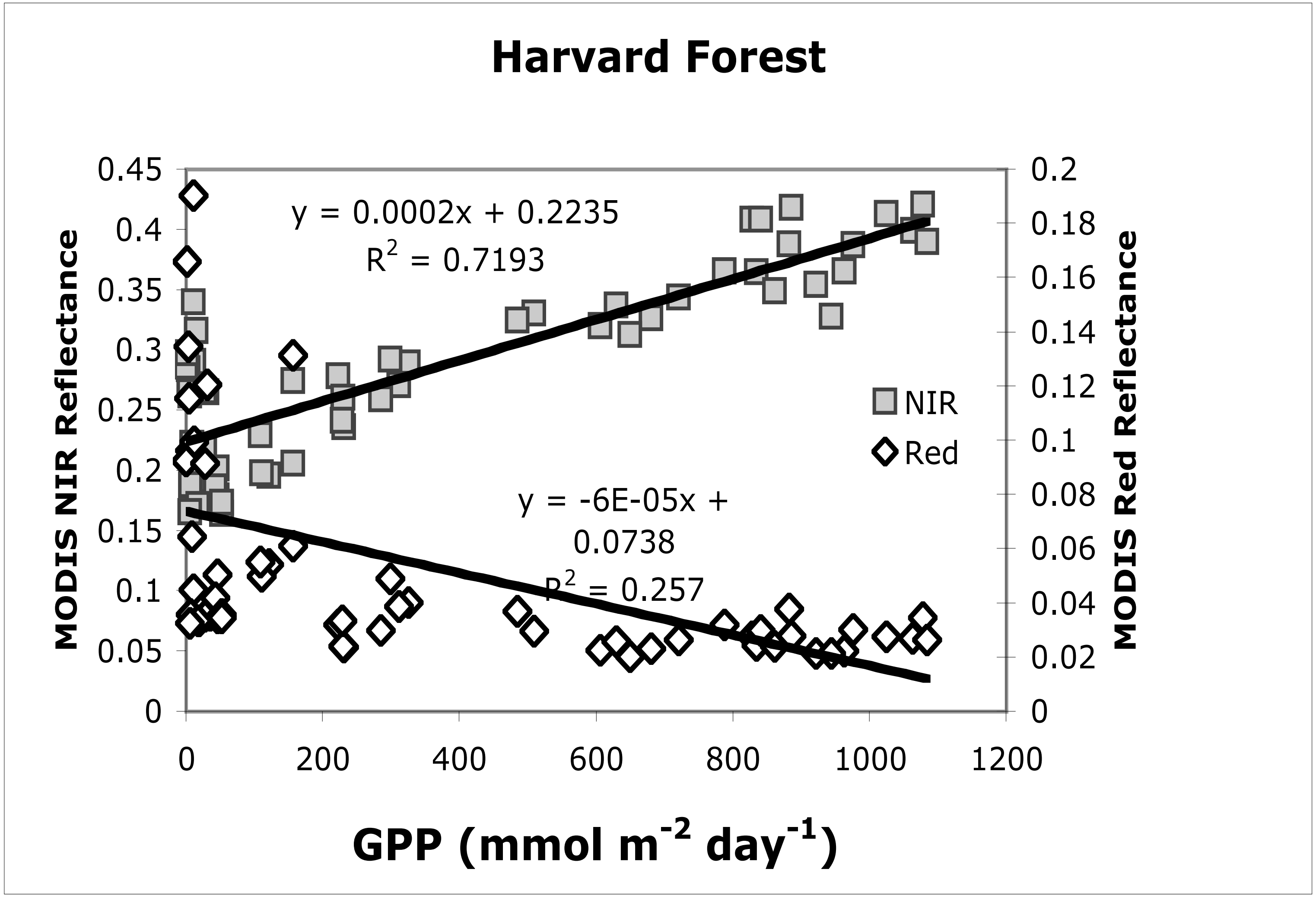
Conclusions

- At regional scales, a complex mosaic of vegetation function and phenology was found as a result of forest structural variations; soil properties, land use activities, conversion and human interactions; variations in climate; and associated ecological conditions.

- Both climatic and human drivers may alter the balance of moisture and sunlight controls on tropical forest phenology and productivity.


Thank You


DOY 307 Yosio sites
Reflectance
0.6
0.5
0.4
0.3
0.2
0.1
0
400
900
1400
1900
2400
Wavelength, nm
Open TRF-Babacu
Dense Primary Forest (km67)
Open Trop Forest (km67)
Open (dark) forest



i. the near-infrared reflectance would be a near-linear indicator of APAR and a near-linear indicator of P_c and $1/r_c$ under stress-free conditions,

Sellers 1987,1992

Conclusions

- Our results indicate the Amazon behaves distinctly different from several common models and intuition about it suggests,
- We found extensive basin-wide flushes of new leaf growth in the sunny dry season, suggesting that sunlight may exert more influence than rainfall on rainforest phenology and productivity,
- This pattern is opposite that encountered for pastures and disturbed forests which are greenner during the wet season and become moisture stressed in the dry season due to their shallower rooting depths.

- The transitional/ drier, southern Amazon forests had weaker or no ‘greenning’ signal in the dry season and may directly have lower photosynthetic capacity due to reduced water availability,
- Both climatic and human drivers, as well as ecological conditions (soils, topography, nutrients) may alter the balance of moisture, sunlight, and biologic controls on rainforest phenology and productivity,
- Enhanced dry season greenning disappeared in disturbed & drier areas which may also be the case for Amazon rainforests during drier El Niño events