Interpreting 250m Moderate Resolution Imaging Spectroradiometer Vegetation Indices in the Colorado Plateau, USA

Final Report

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Michael A. White[1*] and Melissa Hamar[1]

[1]Department of Aquatic, Watershed, & Earth Resources, Utah State University, Logan, Utah, 84322-5210, USA.

[*]Corresponding author
mikew@cc.usu.edu

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Abstract

The National Park Service (NPS) Vital Signs Monitoring program is an aggressive effort to track ecosystem status in the 270 park units. For large and remote parks, remote sensing may be used as an early warning system to detect anomalous vegetation conditions. Here, we evaluated the ability of the Moderate Resolution Imaging Spectroradiometer 250m Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and red, near infra-red, and blue channels to represent relative ground-measured vegetation conditions. Using an AccuPAR LP-80 PAR/LAI Ceptometer, LAI-2000 Plant Canopy Analyzer, and First Growth digital camera, we sampled plant area index (PAI) and green fractional cover (GFC) at 4 sites along a bioclimatic gradient representing semi-arid woodland, mixed grassland/shrubland, and grassland plant functional types. In 14 visits from June 2005 to October 2005, we intensively sampled each site at a spatial resolution directly comparable to 4 MODIS pixels. PAI was always less than 1.0 and often less than 0.4 and GFC was rarely greater than 5%. Likely due to such low plant cover and instrument noise, correlation coefficients between instruments were rarely significant. From both ground and MODIS data, the woodland site showed little evidence of phenological variability. For the other sites, all with a deciduous grassland component, the LP-80 was significantly and consistently related to NDVI (r^2 0.57 to 0.79, slope 0.76 to 0.89) and less consistently to EVI. In spite of minimal base and amplitude of PAI and NDVI, it appears that MODIS NDVI is capable of resolving extremely subtle changes in herbaceous plant canopies and is therefore a promising tool for use in the Vital Signs Monitoring program.

1 INTRODUCTION

The goal of the National Park Service (NPS) Natural Resource Inventory and Monitoring programs is "…to acquire the information and expertise needed by park managers in their efforts to maintain ecosystem integrity …" (http://www1.nature.nps.gov/protectingrestoring/im/inventoryandmonitoring.cfm). In particular, the NPS is committed to Vital Signs Monitoring in which "Vital signs are measurable, early warning signals that indicate changes that could impair the long-term health of natural systems" (http://www1.nature.nps.gov/protectingrestoring/IM/vitalsignsnetworks.cfm). The NPS has organized the 270 park units into 32 monitoring networks, each of which is responsible for developing their own approach to Vital Signs Monitoring.

The Northern Colorado Plateau Network (NCPNN) and Southern Colorado Plateau Network (SCPNN) include some of the largest parks in the lower 48 states, regions of which are difficult to monitor with ground-based observations. Satellite remote sensing is therefore an attractive alternative with which to monitor park resources. The Moderate Resolution Imaging Spectroradiometer (MODIS [*Running et al.*, 1994]), carried on satellites with both morning (AQUA) and afternoon (TERRA) overpass times, provides the ability to monitor 37 channels with daily time resolution and 250m (red and near infra-red, NIR), 500m, and 1km resolutions. In practice, due to cloud and atmospheric contamination, raw daily data is used rarely and a compositing procedure is implemented [*Holben*, 1986]. For monitoring vegetation conditions, vegetation indices such as the normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) are often used. Although technical and conceptual issues exist [*Baret and Guyot*, 1991; *Elvidge and Chen*, 1995] and results may differ among sensor [*Wang et al.*, 2005], NDVI is related to the fraction of photosynthetically active radiation absorbed by plant canopies [*Asrar et al.*, 1984] and leaf area index (LAI [*Myneni et al.*, 1997; *Spanner et al.*, 1990]). The EVI includes the blue channel to reduce atmospheric contamination and a consideration of soil effects [*Huete et al.*, 2002]. In contrast to other sensors requiring extensive user-conducted atmospheric corrections (such as the advanced very high resolution radiometer, AVHRR) [*Pinzon et al.*, 2005; *Slayback et al.*, 2003], high quality, atmospherically corrected vegetation indices are produced for MODIS.

While the absolute values of MODIS products have been intensively validated [*Gao et al.*, 2000] for specific sites and specific dates, validation of time-series data is comparatively rare. Huemmrich et al. [2005] and Fensholt and Sandholt [2005] conducted MODIS validations in Africa but these sites were much more densely vegetated and/or were monitored with point-based ground observations. Kawamura [2005] compared productivity measurements to MODIS data but for each site used only 3 ground observations at 5 points. To our knowledge, no validation or evaluation of MODIS time-series data exists for semi-arid vegetation in which ground data was collected at a spatial resolution corresponding to MODIS pixels.

Our goal was therefore to compare time-series of ground-based plant area index (PAI) and green fractional cover (GFC) against MODIS data at sites along a bioclimatic gradient spanning the NCPN and SCPN. Note that in contrast to research requiring absolute magnitudes of EVI, NDVI, or derived variables, our research is designed to test whether or not MODIS-based 250m data is related to relative changes in ground conditions. To accomplish our goal, we implemented a cyclic sampling design and intensively sampled 4 sites, each of which corresponded to 4 MODIS pixels; we sampled each site 14 times from late June 2005 to mid-October 2005. We compared ground conditions to EVI, NDVI, and channel data and evaluated the ability of MODIS to represent relative, within-site phenological patterns.

2 METHODS

2.1 Site descriptions

We conducted our comparison of satellite and ground-based phenology in the Colorado Plateau physiographic province (Figure 1). The Colorado Plateau is an unusually thick, uplifted, and minimally deformed portion of the Earth's crust. The thick sedimentary rock sequence includes Precambrian igneous, metamorphic, and sedimentary layers exposed in some deep canyons such as the Grand Canyon, West Water Canyon, and the Canyon of Lodore. The youngest rocks (Tertiary or younger) are the sedimentary and volcanic layers capping the high plateaus of Utah and isolated regions in northern Arizona. The sedimentary rock sequence that is now exposed at the surface gives rise to topographic variations in which weak erodible rocks underlie valleys, i.e. the Gunnison valley underlain by the Mancos Shale, and resistant rocks underlie some areas of high terrain, i.e. the Paleozoic and Mesozoic layers of the San Rafael swell. Overall topography is complex with frequent mesas, plateaus, and mountains and elevation ranging from 1500 m to over 3500 m. Well-defined faults create clear boundaries between the Colorado Plateau and the Basin and Range province to the West and South; northern and eastern boundaries, created by the Rocky Mountains, are more diffuse. Only the high plateaus of UT and the isolated volcanic mountains receive significant winter snow. Runoff in the moderate-sized streams of the central and southern half of plateau typically occurs during the summer and fall thunderstorm season when monsoonal circulation dominates the region. Flood magnitudes of the largest inter-regional rivers, such as the Green River and upper Colorado River are determined by the magnitude of the winter snowpack in the adjacent Rocky Mountains. Soil development is minimal in most areas and thus vegetation patterns are determined strongly by the underlying bedrock.

In collaboration with National Park Service staff, we identified 4 study sites representing a continuum of semi-arid vegetation types found throughout the Colorado Plateau: woodland; grassland with shrubs; shrubland with grasses; and grassland. For several reasons, site selection was non-random. First, due to time and budgetary constraints, we required sites to be near roadways. Second, we sought to identify sites with homogeneous landcover. Third, we required sites in which the physical site dimensions corresponded with MODIS pixel locations. Sites are described below and in Table 1.

2.1.1 Bureau of Land Management (BLM)

BLM represents the woodland vegetation type. The site is located east of Utah highway 313 approximately 3km north of the Canyonlands National Park boundary. Topography consists of gently rolling hills and rocky outcrops with an elevation range of approximately 30m. Vegetation is an open woodland canopy dominated by *Pinus edulis* (piñon pine) and *Juniperus osteosperma* (Utah juniper). Understory vegetation is sparse and consists of *Artemesia tridentata* (big sage), *Ephedra viridis* (Mormon tea), *Ericameria nauseosa* (rubber rabbitbrush), *Oenothera* spp. (evening primrose), and *Opuntia* spp. (pricklypear cactus). Biological soils crusts are common. Site disturbances include all terrain vehicle and motorcycle recreation accessed through numerous dirt roads and tracks, flash floods occurring in multiple washes, and cattle grazing. At BLM, our initial intent was to conduct a sampling strategy to isolate the phenological variation of understory and overstory vegetation. However, once plot layout (see below) was complete, we found that less than 5 plots had both overstory tree cover and extant herbaceous or shrubby understory cover. We therefore did not attempt a sampling strategy to separate overstory and understory phenology.

2.1.2 Canyonlands National Park (CANY)

CANY represents the grassland with shrubs vegetation type, i.e. the site is primarily grassland but contains significant shrub cover. The site is located east of Utah highway 313 in Gray's pasture in the Island in the Sky portion of Canyonlands National Park. Topography consists of gently rolling hills with an approximate 30m elevation amplitude. Vegetation consists of sparse grassland dominated by *Hespeostipa comata* (needle and thread grass) and *Achnatherum hymenoides* (Indian rice grass). Isolated individual *Ephedra viridis* and *Juniperus osteosperma* occur throughout CANY. A clearly marked hiking trail is adjacent to the measurement area with limited or no evidence of trespassing beyond trail boundaries. While natural disturbances may have occurred in the past, there is no visual evidence of further anthropogenic disturbance and the site does not contain invasive species.

2.1.3 Petrified Forest National Park (PEFO)

PEFO represents the shrubland with grasses vegetation type, i.e. the site is primarily a shrubland but contains significant grass cover. The site is located east of the main park access road and approximately 500 m south of US interstate 40. Topographical variation is limited with a 9 m elevation range across shallow slopes near the main park road. Vegetation consists of a sparse shrubland dominated by *Atriplex canescens* (four-winged saltbush), *Pleuraphis jamesii* (galleta grass), *Bouteloua eriopoda* (black grama grass), and *Gutierrezia sarothrae* (snakeweed). Disturbance issues include historical grazing, Native American occupation (potshards found on-site), and pre-interstate travel routes. The invasive grass *Bromus tectorum* (cheatgrass) exists in Petrified Forest National Park but was limited in the study site.

2.1.4 Wupatki National Monument (WUPA)

WUPA represents the grassland vegetation type and is a rare example within the National Park System of nearly pure grassland with limited or no evidence of invasive species. The site is approximately 500m north of the Coconino National Forest boundary, 1.5km east of Arizona highway 89, and 500m north of Forest Service road 5632. Topographical variation is limited with a 9m elevation range across gently rolling hills. Vegetation consists of *Pleuraphis jamesii*, *Gutierrezia sarothrae* (snakeweed), and *Salsola tragus* (prickly Russian thistle), *Bouteloua eriopoda*, and *Ericameria nauseosa*. Disturbance issues include motorized recreation via Forest Service roads. Native American settlement was extensive (at least two archaeological sites within the site and extensive potshards).

2.2 Ground Sampling

2.2.1 Sampling Design

At each site, we implemented a ground-based cyclic sampling design [*Burrows et al.*, 2002; *Clinger and Van Ness*, 1976] to correspond to a 2x2 grid of 250m MODIS pixels in the Lambert's Azimuthal Equal Area (LAZEA) projection used by Earth Resources Observation & Science Data Center (EDC) (Figure 2). The cyclic approach is designed to produce pairs of points at all distances (important for variograms) while maintaining an easy to navigate and efficient layout. The cyclic design will leave portions of the site unsampled and is thus not ideal for interpolating complete spatial coverage based on ground data. Within each pixel, we assigned a 17x17 plot layout. For ease in future LANDSAT comparisons, each plot was 14.25 m on each side. Based on this layout, plots in the far right column and bottom row in each MODIS pixel were 22 m. At each plot, we sampled 4 subplots cardinally oriented around the center of each plot. To summarize terminology, site refers to BLM, CANY, PEFO, or WUPA; pixel refers to a 250m MODIS pixel within a site; plot refers to a 14.25 m plot within a pixel; and subplot refers to the location of a single ground observation within a plot (Figure 2).

For all sites, we located and marked plot and subplots as follows. First we obtained the Easting/Northing of the upper left corner of each site (B. Reed, personal communication). From this coordinate, we navigated to the center of each plot using a Trimble GeoExplorer CE with TerraSync 2.3 (Trimble Navigation Limited, 7403 Church Ranch Blvd, Suite 100, Westminster, CO 80021, USA). We used Universal Transverse Mercator (UTM) zone 12, real time settings, integrated Wide Area Augmentation System, and the North American Datum of 1983. We marked plot centers with an 8d nail, or, for cases in which the nail was repeatedly lost, obscured, or otherwise unusable, a wire flag.

For all instruments, we followed a systematic sampling design following the layout shown in Figure 2. We measured plots 1 to 25 in pixel 1 followed by an identical plot sampling in pixels 2 through 4. Data was recorded with such that each plot had a unique identification.

Our goal was to sample each site every 7 days. We maintained a schedule very close to this goal with the exception of early in the field season while we refined sampling methods, during a work break in mid-August, and during some hazardous weather conditions. For all sites we recorded a total of 14 sites visits ranging from late June to early October of 2005. See Table 2 for a complete listing of site visits.

2.2.2 Sampling considerations

With the exception of BLM, we sampled in National Park Service land, in which strict regulations must be followed. We avoided damaging biological soils crusts; removed nothing from the sites; traveled to plots using the same travel pathways (and same footprints, when possible); and did not destructively sample any plant material.

2.2.3 Ocular Measurements

At each site visit we visually assessed the dominant three species. Beginning with visit 9 or 10, we used the GLOBE green-down protocol (www.globe.gov) to measure plant senescence. We identified individuals of the three dominant species and assigned a GLOBE color to the live component. We visually estimated the percent of the plant with this color (the live component); the residual is the senescent component. Budburst or green-up occurred prior to the initiation of fieldwork and was not measured.

2.2.4 Plant Area Index (PAI)

We measured PAI with the AccuPAR LP-80 PAR/LAI Ceptometer (Decagon Devices, Inc. 950 NE Nelson Court, Pullman, WA 99163, USA) and the LAI-2000 Plant Canopy Analyzer (LI-COR, Inc. 4421 Superior St. Lincoln, Nebraska 68504, USA). For this study, PAI as measured by the LP-80 and LAI-2000 is inclined projected PAI, silhouette PAI, or effective PAI, and represents the projected area of leaves taking into account individual leaf inclinations [*Huemmrich et al.*, 2005] and has units of m^2/m^2. Despite advertising to the contrary, the LP-80 and LAI-2000 record a measurement of PAI, including all live and dead woody and non-woody canopy components, not LAI. It is possible to correct for live:dead ratios and canopy clumping;

these techniques, though, require destructive sampling which we were unable to pursue within the parks.

The LP-80 integrates photosynthetically active radiation (PAR, 400-700nm) along 80 individual PAR sensors spaced at 1cm intervals. The unit includes an integrated datalogger and an external PAR sensor. Full details on the theory and operation of the unit are available from the manufacturer [*Decagon Devices*, 2003]. Briefly, PAR measurements above and below the canopy are compared and a radiative transfer model is used to invert PAI. Improvements over prior iterations of the instrument include an ability to correct for local solar zenith angle, onboard calculation of PAI, and an external PAR sensor, which, in theory, simplifies the collection of above canopy PAR data. Also, the user may specify a leaf distribution parameter (χ) describing the ratio of the length of the horizontal to the vertical axis of the spheroid described by the leaf angle distribution of the canopy [*Decagon Devices*, 2003]. χ is defined by measuring above- and below-canopy PAR at the same location over several hours; assuming no changes in cloud cover, differences in measurements are a function of leaf distributions. At the initiation of field work, we measured PAR at each hour from 11 AM to 7 PM and then performed manufacturer-specified calculations [*Decagon Devices*, 2003] to establish χ (BLM = 2.18; CANY = 1.87; PEFO = 1.44; WUPA = 1.87). We used these χ values for all LP-80 PAI calculations.

We sampled with the LP-80 +/- 3 hours of solar noon in clear sky conditions. When the external PAR sensor was functioning, we recorded simultaneous above- and below-canopy PAR at each of the 4 subplots at each plot and then recorded PAI in the internal datalogger. We calibrated the LP-80 and the external sensor at each visit and as needed within visits. The external sensor failed repeatedly, due mostly to manufacturing defects in cable connections and housing. When this situation existed, we recorded 1 above-canopy PAR value, 4 below-canopy

PAR values at the subplots, another above-canopy PAR value, and then calculated and recorded PAI.

The LAI-2000 measures diffuse sky radiation simultaneously at 5 zenith angles. As for the LP-80, measurements are taken above and below the canopy and a radiative transfer algorithm is used to invert PAI [*LI-COR*, 1992]. In sparse or clumped canopies, as at the BLM woodland site, it is possible that the sensor will simultaneously view dense canopy and open space, potentially producing erroneous calculations. Following Appendix D in the operator manual [*Norman et al.*, 1995], we therefore conducted the canopy gap test and found that for all sites, use of the LAI-2000 without view caps was acceptable. Ideally, PAI calculations are based on below-canopy measurements from one instrument and above-canopy measurements continuously logged by a remote unit. The two data streams are then combined in post-measurement processing to calculate PAI. Due to (1) the number of samples taken, (2) a critical requirement of diffuse radiation conditions (pre-dawn or post-sunset), and (3) the desired site repeat cycle, we were forced to use both units for field measurements. In this approach, at each plot we took 1 above-canopy measurement followed by 4 measurements at the subplot locations. In two cases at BLM, we used the LAI-2000 in pre-dawn conditions; otherwise we collected data immediately prior to or after sunset. We continued to take measurements until radiation readings were less than 5 times the sensor noise (established under no-light conditions). For cases in which measuring only after sunset would have necessitated another day at the same site, we measured prior to sunset and shaded the sensor with the operator's body and used a 45° view cap to hide the operator from view.

For both the LP-80 and LAI-2000, it is important to note that our observations are relative measurements of PAI. Calculation of actual LAI would have involved extensive and repeated destructive sampling. Thus, PAI values are comparable only within sites; i.e. due to variation in live:dead ratios, foliage clumping, and degree of woodiness, a PAI value of 0.5 at BLM is not directly comparable to a PAI value of 0.5 at WUPA. A side effect of this sampling design is that violations of instrument assumptions are generally immaterial, as they will be constant or nearly constant across site visits.

2.2.5 Green Fractional Cover

We used the First Growth Digital Canopy Camera (Decagon Devices, Inc. 950 NE Nelson Court, Pullman, WA 99163, USA) to measure GFC [*Decagon Devices*, 2004], recorded as a percent of total ground cover. The First Growth unit is similar to standard digital camera using interlaced charged coupled devices. Specifications include 640 x 480 pixels resolution; 24-bit color; 8.5mm lense; *f*/1.5 to *f*/16 aperture; and 1/10,000 second to 1/30 second shutter speed. There are two advantages to using the First Growth over traditional digital cameras: (1) the ability to conduct in situ white balance corrections to adjust for variation in illumination conditions; and (2) calculation of GFC within the camera itself (using an internal cutoff value based on Munsell Color charts). The First Growth is not a state-of-the-art camera; modern commercial cameras have superior resolution and optics and have been used to calculate GFC in programs such as Adobe Photoshop. Manual processing of the thousands of images we collected would have been impracticable.

In the field the First Growth unit proved to be unwieldy and difficult to use. We intended to measure all 4 subplots, as for the LAI-2000 and LP-80, but camera imaging and storage onto flash memory rendered this impossible within our time frame (imaging 400 subplots, as intended, would have taken several days per site visit). We therefore recorded only 1 image at the northern subplot. Further, due to terrain variation, the intended manual leveling of the camera with a tripod at each subplot was excessively time-intensive; instead we conducted hand-held camera imaging in motion mode [*Decagon Devices*, 2004]. We white balanced the camera at each site visit and, if variations in illumination conditions occurred, within site visits. We recorded the camera-calculated GFC values and archived images as RGB tiff files. We then used a supervised classification to classify First Growth RGB images into site-specific landcover classes. We used the ENVI 4.0 (Research Systems, Inc., Boulder, CO 80301, USA) Region of Interest (ROI) tool to manually identify polygons containing specific landcover classes. We found that while it was possible to construct ROI that would produce accurate landcover classifications for an image or group of images, misclassifications increased unacceptably between pixels and or site visits. Ultimately, manual classification of a high percentage of the 5000+ First Growth images would be required. Given the extensive problems with the First Growth (section 4.2) we did not pursue this approach.

2.3 MODIS Remote Sensing

We designed our ground-based sampling to generate comparisons with 4 MODIS 250m pixels, as reprojected from the native MODIS sinusoidal projection to the EDC LAZEA projection, but were forced to use an alternate remote sensing product. EDC produces a rolling composite product in which for every day and every pixel, the maximum value from the previous 8 days is selected. This approach is potentially superior to the traditional maximum value compositing procedure, in which a single value is produced for a given time period [*Holben*, 1986]. Due to reprocessing requirements mandated by errors in the prior terrain correction module, the rolling composit data were not available for this study. Consequently, we obtained the MODIS 16-day vegetation index products (generated with a view angle constrained compositing process). We obtained both AM (MYD13Q1, AQUA satellite) and PM (MOD13A1, TERRA satellite) data from the EDC data gateway. All sites were contained in either the horizontal 08/vertical 05 or horizontal 09/vertical 05 tiles in the MODIS sinusoidal projection.

We implemented a 4-step processing algorithm to generate a time-series of MODIS data for each site. First, we converted the GPS UTM coordinates of each plot center to decimal degrees of latitude and longitude using the ENVI ASCII Coordinate Conversion function. Second, we used a sequence of EOS_GD functions in IDL 6.0.1 (Research Systems, Inc., Boulder, CO 80301, USA) to identify the 250m pixel containing each plot center. Third, we extracted NDVI, EVI, red, NIR, and blue data for each plot and created separate site average value for AQUA and TERRA satellites. In essence, as our plot layout occurred unevenly on more than 4 MODIS pixels, we generated an area-weighted site average. Fourth, to further reduce potential atmospheric and cloud contamination, we calculated an AQUA/TERRA composite by selecting the maximum NDVI, EVI, and NIR and minimum red and blue values (higher vegetation cover is associated with high vegetation index and NIR but lower red and blue). We repeated these steps for the 8 16-day composite periods in which we collected ground data.

2.4 Analysis

We conducted 3 general analyses to assess: (1) the relationship between ground-based PAI and GFC phenology measured with the LAI-2000, LP-80; and First Growth; (2) quantitative analysis of the relationships between ground and MODIS data; and (3) qualitative phenological patterns in ground- and MODIS-based data.

2.4.1 Ground-based PAI and Green Fractional Cover

One goal of our research was to conduct an intercomparison of measurements of the 3 instruments. We first compared instrument mean and coefficient of variation (CV, standard deviation/mean) across site visits. As prior research has indicated that data from the LAI-2000 and an instrument nearly identical to LP-80 are essentially interchangeable [*White et al.*, 2000a], we conducted t-tests, for each site visit, between PAI measured with the LAI-2000 and LP-80 (First Growth not compared as GFC is physically different than PAI). We next expanded this test and evaluated instrument relationships over the 14 measurement dates at each site by calculating linear regression equations and r^2 (coefficient of determination) values (regress function, IDL 6.0.1, RSI, Boulder, CO) for: LAI-2000 versus LP-80, LAI-2000 versus First Growth; and LP-80 versus First Growth. For these regression comparisons, and also for comparisons of ground data versus satellite data, as our goal was to assess the instruments' ability to represent relative changes in phenological metrics, not absolute values, we used standardized anomalies, or z-scores:

$$Z = \frac{x - \bar{x}}{\sigma}$$

where x is the mean of one of the site visits, $\bar{x}$ is the mean from the 14 site visits, and σ is the standard deviation of the 14 site visits.

2.4.2 Quantitative Analysis of Ground Versus MODIS data

We compared ground-based data (PAI and GFC) versus MODIS data (EVI, NDVI, red, NIR, blue). For the 7 or 8 composite periods, we averaged the corresponding ground-based data and conducted two regression analyses: (1) the three ground metrics versus the five remote sensing metrics; and (2) ratios of PAI:GFC versus the five remote sensing metrics. In order to assess possible interactions between spatial patterns of ground observations and ground-to-MODIS correlations, we fit exponential and spherical variogram models to the sample variogram and calculated the range, partial sill and nugget using the vgm, variogram, and fit.variogram functions in the gstat spatial statistics package (http://www.gstat.org) in R (version 1.12 (1622), R Foundation for Statistical Computing). We finally assessed whether or not the timing of minimum and maximum ground-based metrics occurred during the same composite period as minimum and maximum EVI and NDVI.

2.4.3 Qualitative Phenology

Our purpose here was to provide a visual depiction of the absolute magnitudes of seasonal phenological patterns. We constructed line plots depicting ground data (LAI-2000, LP-80, First Growth) and MODIS EVI, NDVI, and channel data (Appendix A).

3 RESULTS

3.1 Ocular Measurements

At all sites, the dominant species were constant among site visits: *Pinus edulis*, *Juniperus osteosperma*, and *Artemesia tridentata* at BLM; *Hespeostipa comata*, *Achnatherum hymenoides* and *Ephedra viridis* at CANY; *Atriplex canescens*, *Pleuraphis jamesii*, and *Bouteloua eriopoda* at PEFO; and *Pleuraphis jamesii*, *Gutierrezia sarothrae*, and *Salsola tragus* at WUPA. At BLM the GLOBE-based analysis showed that at all visits, the live percentage was constant (Table 3). At CANY, while *Ephedra viridis* was constant at 90-95%, the grass species live percent varied throughout the season. Visits 9 – 11, though had a higher live percent than visits 12 – 14. At PEFO and WUPA, live percent declined from visit 9 to 14.

3.2 Instrument Performance

We experienced failure or malfunction with all instruments. During visit 9 at PEFO one of the LAI-2000 units failed due to a loose screw contacting an internal fuse and we were unable to measure pixels 3 and 4 on visit 9. For all sites on visits 10 and 11 we elected to measure only pixels 3 and 4. In an attempt to fill missing observations, we experimented with generating correlations between pixels 1 and 2 and pixels 3 and 4 during visits 9 and 12. Correlation coefficients were low (r^2 approximately 0.3) and we elected not to fill missing observations.

As discussed above, the external sensor for the LP-80 was unreliable and required two repairs before the manufacturer noted a flaw in the engineering design. The LP-80 data download cable broke after visit 5 and the instrument was repaired during visit 6. Data downloads from the LP-80 required extensive manual postprocessing to eliminate duplicate records. The First Growth camera failed to record 5-10% of images and occasionally recorded images as jpeg, not the specified tiff format. Depending on solar orientation, images were differentially shadowed by the overstory canopy (BLM) or the operator; we could have shifted operator position to avoid shadow but this would have conflicted with our NPS mandate to minimize soil disturbance and would have changed viewing geometry among repeat images. The effects of shadowing were most pronounced in bright illumination conditions causing high contrast and unrealistic values for GFC. We therefore manually screened the 5000+ images. This process was subjective: we compared images with high contrast to temporally adjacent images with low contrast and removed values for which GFC was clearly unrealistic. We removed 44% of images in BLM; 36% in CANY; 25% in PEFO; and 31% in WUPA.

All instruments were problematic to use with circa 2005 computers. All cable interfaces required adapters and software was often incompatible with operating systems. Li-Cor and Decagon have made little effort to update hardware and software and usability is correspondingly reduced.

3.3 Ground-based PAI and Green Fractional Cover

For PAI, 5 general patterns existed (Figure 3): (1) site-average PAI was below 0.9 at all sites and all visits; (2) BLM had the highest PAI and showed no consistent patterns of seasonality (ANOVA p-value < 0.05 for LP-80 but 0.13 for LAI-2000); (3) except for BLM, the LAI-2000 recorded higher PAI than the LP-80; (4) for CANY and PEFO, both instruments recorded seasonal minima around visit 3 (mid-July) preceded and followed by higher PAI; (5) except for a high LAI-200 value on visit 1, WUPA PAI was extremely low from both instruments but showed a slight trend towards higher late season values from the LP-80.

Green fractional cover was extremely low for all sites and never exceeded 15%. Beneath the tree canopy, BLM was essentially bare soil with only sporadic occurrences of green fraction cover greater than 1%. At CANY, the First Growth showed evidence of a late season increase similar to the LP-80. WUPA was clearly different than other sites and had 5 of 14 values above 10% green fractional cover. Further, WUPA had the highest GFC with the lowest PAI, indicating that a higher proportion of vegetation was green at any one time in WUPA than in other sites.

Instrument CV for the LAI-2000 and LP-80 was between 0.25 and 1.5 and generally similar between the instruments, except at BLM, where LP-80 CV was consistently higher (Figure 3). First Growth CV was greater than 3 for most site visits at BLM but more closely resembled LAI-2000 and LP-80 CV at the other sites, especially WUPA.

Comparisons of mean PAI values recorded by the LAI-2000 and LP-80 varied by site. At BLM, PAI from the LAI-2000 and LP-20 was statistically identical in 11 of 13 site visits (t-test, 5% significance level, visit 6 excluded due to LP-80 failure). In contrast PAI was statistically different in 12 of 13 visits at CANY, all visits at PEFO, and 11 of 13 visits at WUPA.

When compared as standardized anomalies, the 3 instruments were usually unrelated to each other (Figure 4). Only three comparisons were statistically significant (F-test, 5% significance level): LP-80 versus First Growth at CANY; LAI-2000 versus LP-80 at PEFO; and LP-80 versus First Growth at WUPA.

3.4 Quantitative Analysis of Ground Versus MODIS data

MODIS data were not consistently related to ground-based metrics (standardized anomalies used, Table 4). In no case was the ratio of PAI:GFC more related to MODIS data than PAI and/or GFC separately and such comparisons are not presented (F-test, 5% level). In no case was MODIS NIR or blue data significantly related to PAI or GFC (F-test, 5% level). At BLM, PAI from the LAI-2000 was related to NDVI with an r^2 of 0.60 but there were no significant differences among PAI observations (section 3.3). With r^2 between 0.57 and 0.79 and slopes near 0.8, the LP-80 was related to: NDVI at CANY, PEFO, and WUPA; EVI at CANY and WUPA; and red at PEFO. The LAI-2000 was also related to EVI and NDVI at PEFO. The First Growth was related to WUPA EVI but was otherwise unrelated to MODIS data.

In summary, the LP-80 produced consistently significant relationships between ground-measured PAI and MODIS NDVI. When visualized as standardized anomalies (Figure 5), PAI from the LP-80 and MODIS NDVI exhibited a close relationship except for yearday 169 at BLM, yearday 265 at CANY, and yearday 281 for PEFO.

Variograms were extremely sensitive to initial parameter estimates; model-fit range could change 2 orders of magnitude based on slight initial variations. We found that each site visit required considerable subjective parameter fitting and selection of exponential versus spherical model types. Ultimately, consistent fitting of variograms across site visits was not practicable and we do not present these results.

The correspondence of the composit period containing seasonal maximum (max) and minimum (min) MODIS versus ground data followed other results (Table 5). At BLM, max/min differed between EVI and NDVI and among the LAI-2000, LP-80, and First Growth. Only max for NDVI and the LAI-2000 was the same. At CANY and PEFO, max NDVI/EVI and PAI/GFC were within 1 composite period of each other; CANY min dates were widely scattered; PEFO min dates agreed within 1 composite period. At WUPA, MODIS dates were identical and were within 1 composit period of max LP-80 and First Growth dates. All WUPA min dates from the ground instruments were at least 2 composit periods earlier than corresponding MODIS min dates.

4 DISCUSSION

The four sites considered in this research are representative of semi-arid vegetation in the Colorado Plateau and are characterized by extremely low PAI, GFC, EVI, and NDVI. Assuming prior measurements of the ratio of PAI to LAI of about 1.5 [*White et al.*, 2000a], LAI in BLM (the highest PAI site) rarely exceeded 0.5. Measured seasonal amplitude was often only 0.2 PAI. MODIS vegetation indices recorded similarly small among-visit amplitude, sometimes of only 0.04 (Appendix A). Given these conditions, our central finding that MODIS NDVI is related to PAI is encouraging.

4.1 Sampling Design

Our intention to fit model variogram parameters to sample variograms was unsuccessful. We speculate that this was associated with the extremely low PAI/GFC in the sites. Small variation of canopy elements in relation to sensor placement caused large variations, especially for PAI. Consequently, variogram parameters were subject to temporally unstable spatial patterns, leading to instability in model fitting. For future studies in semi-arid vegetation, there appears to be no advantage to the cyclic design and we recommend a traditional and more familiar line-transect or systematic design. In denser canopies less subject to variation in field sampling conditions, the cyclic design may provide the ability to construct variogram parameter time-series.

4.2 Instruments

The LAI-2000, LP-80, and First Growth were related to each other only rarely (Figure 4). In spite of general statistical similarity within site visits (section 3.3), BLM had no significant relationships among instruments. BLM, though, is essentially bare soil with a sparse evergreen overstory; the lack of clear seasonal patterns was consistent with field impressions. At the other sites, LAI-2000 PAI was higher than LP-80 PAI. This is consistent with instrument theory, in which the LP-80 measures vertical or near-vertical radiation transmission while the LAI-2000 integrates multiple view angles. In more erectophile canopies, the LAI-2000 should therefore record higher values. The First Growth camera was statistically related to the LP-80 at CANY and WUPA but tended to produce variable seasonal patterns; at WUPA, GFC varied by almost a factor of 4. At BLM, where most of the canopy was above the camera, the First Growth measured either bare ground or sparse vegetation, resulting in high CV (Figure 3).

As our study is based on relative values (validation and absolute magnitudes would have required destructive sampling) we are unable to provide conclusive instrument recommendations. However, we state the following 3 qualitative conditions in favor of the LP-80. (1) With the exception of BLM, the LP-80 produced smoother seasonal patterns than the LAI-2000 or First Growth. Based on field observations, vegetation conditions followed generally smooth progressions, as characterized by the LP-80, rather than the sharp drops and rises often recorded in the LAI-2000 and First Growth. (2) The LAI-2000 is highly constrained to dawn/dusk conditions, which can cause logistical difficulties, especially with such an intensive observation program. Afternoon and evening thunderstorms were unusually active and violent in 2005. Even though we sampled near dusk, we believe that this may have caused within- and among-visit variation in illumination conditions sufficient to reduce the relationship between the LAI-2000 and MODIS data. (3) The First Growth is best suited to monitoring crop emergence from bare ground in flat conditions; for field research involving large numbers of observations, it is unwieldy, slow, unreliable, impracticable to use in terrain with even limited topography, and cannot be used to image woodland canopies from above. Camera documentation indicates that suboptimal results may be obtained from: sharp pixel-to-pixel color and/or brightness contrast; images with large brightly illuminated and highly shadowed regions (First Growth cannot produce an exposure setting to minimize shadowed/illuminated contrasts); bright, dry soils; and the presence of trash (common at Wupatki) or gravel. We experienced all these conditions.

Ideally, we would have used a light diffusing material over every image and manually wetted the soil before each image but this would have been prohibitively time-consuming. In short, we recommend that the First Growth should not be used for similar studies in the future.

4.3 Relationship of MODIS Data to Ground Conditions

In spite of the limited phenological variability present from both the LP-80 and MODIS, we found consistently significant relationships between ground-based LP-80 PAI and MODIS NDVI (Table 4). With the exception of BLM, where vegetation conditions were essentially constant over the study period, phenological patterns between the LP-80 and MODIS NDVI were remarkably similar (Figure 5). At CANY, PEFO, and WUPA, the general PAI/NDVI decline in late June, low levels throughout most of July, and increasing levels in late summer were consistent with warm season senescence after spring growth and subsequent regrowth following heavy monsoonal precipitation in late summer of 2005. For LP-80 overestimates in October (Figure 5), we speculate that a relatively large yet already senescing canopy existed, as suggested by decreases in the live canopy percentage beginning around visit 12 (Table 3). Errors were largely confined to this period and we conclude that on a relative basis and for sites with at least a small deciduous herbaceous canopy, MODIS NDVI is related to ground-based patterns of vegetation phenology in the sampled semi-arid plant functional type.

Our data strongly suggest that seasonal variations in MODIS NDVI are not spurious artifacts of atmospheric contamination or variation in soil moisture content. Rather, it appears that the MODIS sensor is capable of resolving, within seasons, extremely small variations in plant canopy structure (Appendix A). Given the known poor technology and lack of atmospheric correction, similar variations from the AVHRR sensor would not be similarly interpreted. Even though EVI was designed partially to correct for variation in soil background, EVI comparisons were not superior to those based on NDVI. Use of EVI may be advantageous in denser canopies, as EVI saturates at higher levels than does NDVI.

4.4 Monitoring Recommendations

Based on our results, we suggest that the following four-part MODIS monitoring strategy may be appropriate in the NCPN and SCPN. First, for evergreen woodland sites with long-lived foliage and a limited deciduous understory, such as BLM, we suggest that observations focus on multi-year assessments in which a rolling composit is constructed over a 3- to 4-year period (approximate leaf longevity of evergreen needle leaf trees [*White et al.*, 2000b]) during snow free conditions (defined by the MODIS snow product [*Hall et al.*, 2002]). Following others [*Breshears et al.*, 2005], we thus submit that for evergreen canopies with limited within-season phenological variation, a longer-term monitoring approach is most appropriate for detecting subtle changes. Of course, for detection of major disturbances, other products, such as MODIS fire [*Justice et al.*, 2002], will be useful.

Second, for grassland and the more common shrubland/grassland mixture, our results suggest that MODIS 250m NDVI is an appropriate within-season monitoring tool. We recommend that a time-series of precipitation and corresponding MODIS NDVI data be constructed for NCPN and SCPN NPS units and that the relationship between precipitation and NDVI be established for individual parks. Lagged effects may be an important consideration [*Goward and Prince*, 1995; *Wiegand et al.*, 2004]. In a monitoring sense, given precipitation and NDVI data, a chi-squared analysis or similar approach may then be used to test the relationship between current and expected conditions. We expect that this approach will be feasible in areas with a PAI of at least

0.15 with grass cover of at least 5%. In order to identify regions appropriate for this technique, the NPS may wish to consider generating a continuous fields classification [*Hansen et al.*, 2003; *Hansen et al.*, 2002] specific to the NCPN/SCPN; existing global products contain extensive biases in the southwestern USA [*White et al.*, 2004].

Third, in the semi-arid grassland/shrubland plant functional type, absolute EVI/NDVI values are so low that extraction of specific phenological dates such as start of season or end of season [*Schwartz et al.*, 2002]will be highly sensitive to slight variations and we recommend against such approaches. Nonetheless, the phenological signature of invasive species may be distinct from native species. To track possible shifts in community structure, we recommend that monthly NDVI should be calculated for the MODIS record. By assessing trends in monthly greenness over time, i.e. tracking March, April, May, etc. separately, NPS managers may be able to identify shifting presence of invasive species.

Fourth, deciduous broadleaf trees (*Populus* and *Betula* sp.) are the most tractable plant functional type for coarse resolution remote sensing [*White et al.*, 1997]. For park areas with such vegetation, extraction of the start of season or end of season should be practicable.

If further ground sampling is required for the NCPN/SCPN or for other research in the Colorado Plateau, we recommend the LP-80. Assuming that the manufacturer is able to resolve quality control problems, the instrument is easy to use and contains important improvements over prior Ceptometers. The illumination conditions required for the instrument (around solar noon) are conducive to the logistics of field collection. As long as direct sunlight is present on the probe and if the external probe is functioning, the LP-80 is also insensitive to variations in viewing conditions (partial cloud cover). In erectophile canopies, the LP-80 will underestimate PAI but this does not appear to affect the instrument's ability to capture relative phenological dynamics. Overall, though, the relationship was good and we submit that the LP-80 is the most appropriate instrument for further research.

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Table 1. Site descriptions: Bureau of Land Management (BLM); Canyonlands National Park (CANY); Petrified Forest National Park (PEFO); and Wupatki National Monument (WUPA). Locations correspond to the upper left corner of the 500m x 500m site.

	BLM	CANY	PEFO	WUPA
Latitude	38.5621153	38.42206898	35.0484816	35.54563136
Longitude	-109.7881007	-109.8347193	-109.7996669	-111.5312316
Elevation (m)	1844	1843	1731	1731
Jan low (°C)[a]	-7.9	-7.6	-6.3	-6.0
Jan high (°C)[a]	3.5	3.6	9.1	8.4
Jul low (°C)[a]	16.1	16.3	14.8	14.2
Jul high (°C)[a]	31.9	32.0	33.1	32.2
PRCP (mm)[b]	290	280	270	330
Soil series[c]	Rizno	Ignacio-Leanto	Clovis-Palma	Tuweep very gravelly loam
Family / higher soils taxonomic classification[c]	Loamy, mixed (calcareous), mesic Lithic Ustic Torriorthents	Ignacio: Coarse-loamy, mixed, mesic Ustollic Camborthids Leanto: Loamy, mixed, mesic Lithic Camborthids	Clovis: Fine-loamy, mixed, mesic Ustollic Haplargids Palma: Coarse-loamy, mixed, mesic Ustollic Haplargids	Fine-loamy, mixed, mesic Ustollic Haplargids

[a]Calculated from 24 monthly minimum/maximum vales extracted from 1980 to 2003 daily temperature values (www.daymet.org, [*Thornton et al.*, 1997]).
[b]1980 to 2003 average total annual precipitation (www.daymet.org, [*Thornton et al.*, 1997]).
[c]http://soildatamart.nrcs.usda.gov/

Table 2. Timing of site visits. Black shading indicates measurement period.

	BLM	CANY	PEFO	WUPA		BLM	CANY	PEFO	WUPA
24-Jun		■			18-Aug				
25-Jun		■			19-Aug				
26-Jun		■			20-Aug				
27-Jun	■				21-Aug				
28-Jun	■				22-Aug				
29-Jun				■	23-Aug				
30-Jun				■	24-Aug		■		
1-Jul			■		25-Aug	■			
2-Jul		■	■		26-Aug				■
3-Jul		■			27-Aug				■
4-Jul					28-Aug			■	
5-Jul	■				29-Aug			■	
6-Jul	■				30-Aug				
7-Jul					31-Aug		■		
8-Jul					1-Sep	■			
9-Jul					2-Sep				■
10-Jul				■	3-Sep				■
11-Jul			■		4-Sep			■	
12-Jul			■		5-Sep				
13-Jul		■	■		6-Sep		■		
14-Jul	■				7-Sep	■	■		
15-Jul	■			■	8-Sep				
16-Jul				■	9-Sep				
17-Jul					10-Sep	■			
18-Jul			■		11-Sep				■
19-Jul			■		12-Sep			■	
20-Jul		■			13-Sep			■	
21-Jul	■				14-Sep				
22-Jul	■			■	15-Sep		■		
23-Jul				■	16-Sep	■			
24-Jul					17-Sep				
25-Jul				■	18-Sep				■
26-Jul			■		19-Sep				
27-Jul		■			20-Sep			■	
28-Jul	■	■			21-Sep				
29-Jul	■				22-Sep		■		
30-Jul					23-Sep	■			
31-Jul				■	24-Sep				■
1-Aug			■		25-Sep				■
2-Aug			■		26-Sep			■	
3-Aug		■			27-Sep				
4-Aug		■			28-Sep				
5-Aug	■			■	29-Sep		■		
6-Aug				■	30-Sep	■			
7-Aug					1-Oct				
8-Aug			■		2-Oct				■
9-Aug		■			3-Oct			■	
10-Aug					4-Oct			■	
11-Aug		■			5-Oct		■		
12-Aug	■				6-Oct	■	■		
13-Aug				■	7-Oct	■			
14-Aug			■		8-Oct				■
15-Aug					9-Oct			■	
16-Aug					10-Oct			■	
17-Aug									

Table 3. Percent of individual plants characterized as live foliage (based on GLOBE green-down protocols).

	BLM			CANY			PEFO			WUPA		
visit	PE[a]	JO[b]	AT[c]	HC[d]	AH[e]	EV[f]	AC[g]	PJ[h]	BE[i]	PJ[h]	GS[j]	ST[k]
9	80	80	90	40	30	95						
10	80	80	90	20	10	90	95	80	95	40	20	80
11	80	80	90	40	70	95	95	80	70	40	20	80
12	80	80	90	20	20	90	80	70	40	20	10	60
13	80	80	90	20	10	90	80	70	35	5	10	40
14	80	80	90	10	15	95	80	70	35	5	10	30

[a]*Pinus edulis*
[b]*Juniperus osteosperma*
[c]*Artemesia tridentate*
[d]*Hespeostipa comata*
[e]*Achnatherum hymenoides*
[f]*Ephedra viridis*
[g]*Atriplex canescens*
[h]*Pleuraphis jamesii*
[i]*Bouteloua eriopoda*
[j]*Gutierrezia sarothrae*
Salsola tragus

Table 4. Linear regression results between ground-based and MODIS data over the available 16-day composite periods (7 for BLM and CANY; 8 for PEFO and WUPA). Shown are r^2 values and slope (in parentheses). Non-significant r^2 values not shown (F-test, 5% significance level). Consistent results for LP-80 versus NDVI shown by gray shading).

	BLM	CANY	PEFO	WUPA
LAI-2000 vs. EVI	-	-	0.53 (0.73)	-
LAI-2000 vs. NDVI	0.60 (0.78)	-	0.51 (0.71)	-
LAI-2000 vs. red	-	-	-	-
LP-80 vs. EVI	-	0.78 (0.88)	-	0.68 (0.83)
LP-80 vs. NDVI	-	0.64 (0.80)	0.57 (0.76)	0.79 (0.89)
LP-80 vs. red	-	-	0.62 (-0.79)	-
First Growth vs. NDVI	-	-	-	-
First Growth vs. EVI	-	-	-	0.57 (0.75)
First Growth vs. red	-	-	-	-

Table 5. Timing of maximum and minimum EVI, NDVI, PAI (LAI-2000 and LP-80) and GFC (First Growth) at the 4 sites. Dates indicate the first day of the 16-day MODIS compositing period.

	BLM		CANY		PEFO		WUPA	
	max	min	max	min	max	min	max	min
EVI	265	185	249	185	249	185	233	281
NVDI	169	217	233	217	233	201	233	281
LAI-2000	169	201	249	201	249	185	169	249
LP-80	249	169	233	201	233	185	233	185
First Growth	201	233	233	169	233	185	217	185

Figure captions

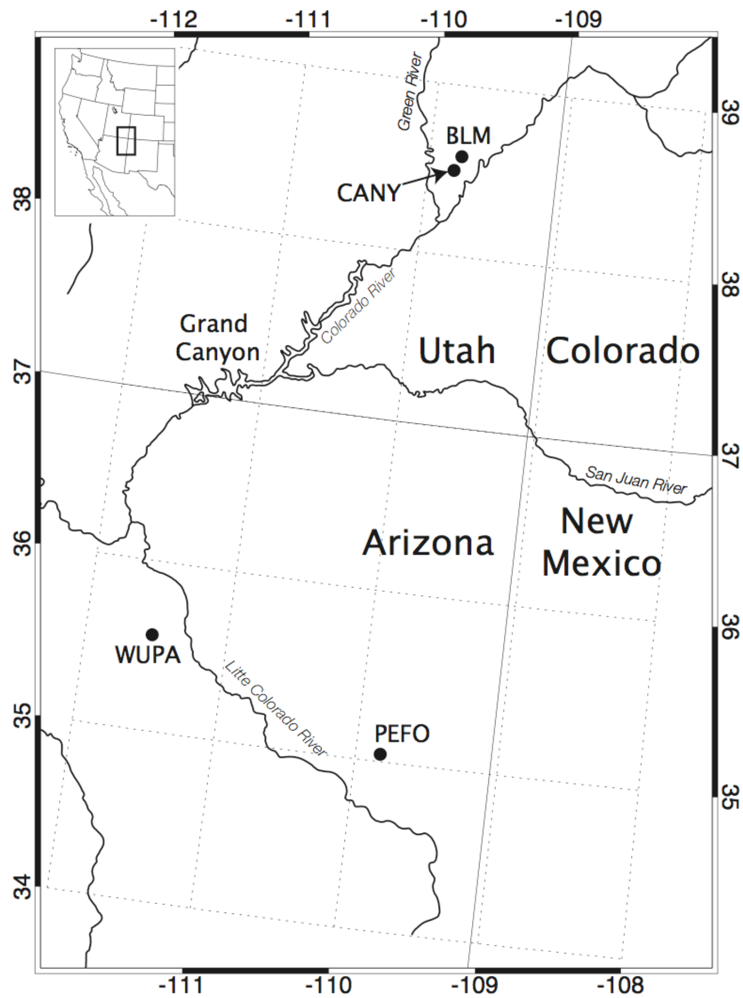
Figure 1. Study region. Sites shown as black circles.

Figure 2. Cyclic sampling design for one site showing the layout of 4 250m pixels designed to overlap with 4 MODIS pixels in the LAZEA projection. Grid shows the plot layout; shaded plots are measurement plots. Expanded plot shows the layout of the four subplots where the LAI-2000 and LP-80 were used (First Growth used at north subplot only). In each pixel, plots in the rightmost column and bottom row are 22 m.

Figure 3. Plant area index (PAI), green fractional cover (GFC), and the coefficient of variation (CV) for 14 visits at the 4 sites. PAI was measured with the LAI-2000 and LP-80; GFC was measured with the First Growth. GFC lost due to hardware malfunction for visit 1 at BLM and CANY. LP-80 PAI not recorded for visit 6 at due to instrument malfunction. See Appendix A for instrument-specific plots with confidence intervals for each visit.

Figure 4. Relationships between standardized anomalies of PAI and/or GFC. Each point represents on site visit (up to 14 per site). Rows show the 4 sites from top to bottom: BLM, CANY, PEFO, WUPA. Regression fits and 1:1 lines are superimposed. Chart titles show site and r^2 values (* if significant at 5% level, F-test).

Figure 5. PAI measured with the LP-80 (dashed line with triangles) versus MODIS NDVI (solid line with circles). All data are standardized anomalies. Dates on the x-axis are the starting dates of the MODIS 16-day compositing periods. LP-80 data show average field values recorded during the composite period (Table 2).



-112
-111
-110
-109
Green River
BLM
CANY
Colorado River
Grand Canyon
Utah
Colorado
San Juan River
Arizona
New Mexico
WUPA
Litte Colorado River
PEFO
-111
-110
-109
-108
38
37
36
35
34
39

Figure 1

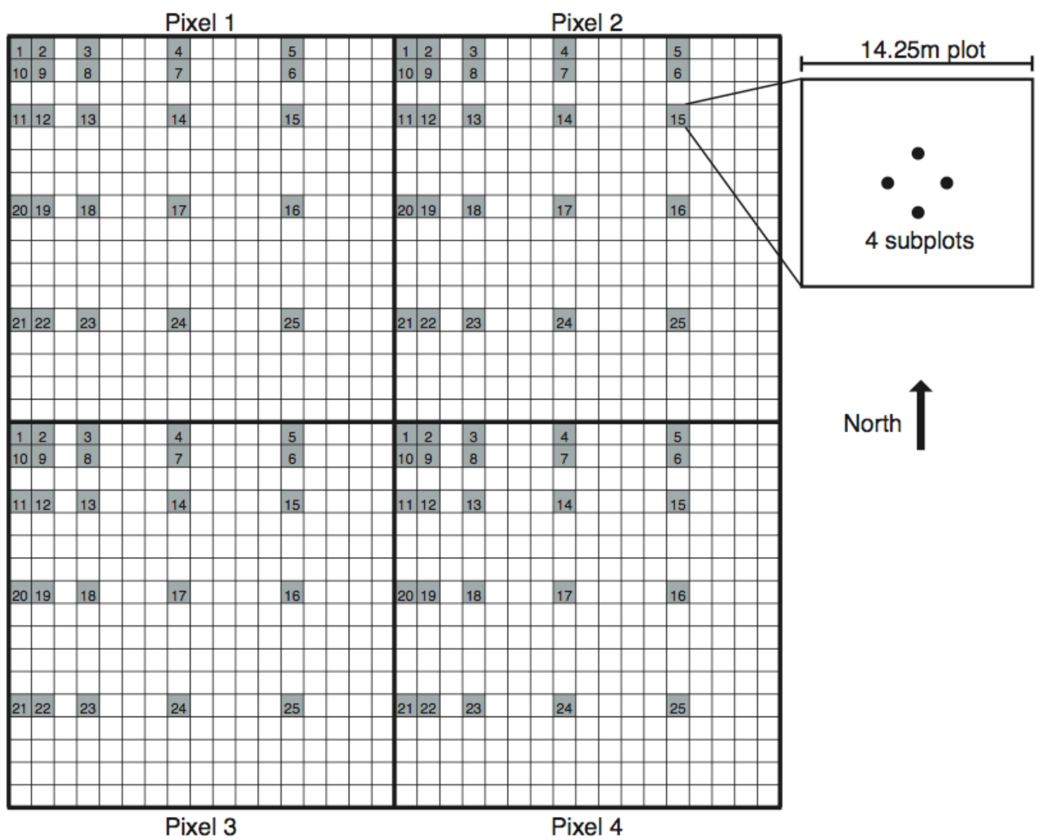


Figure 2

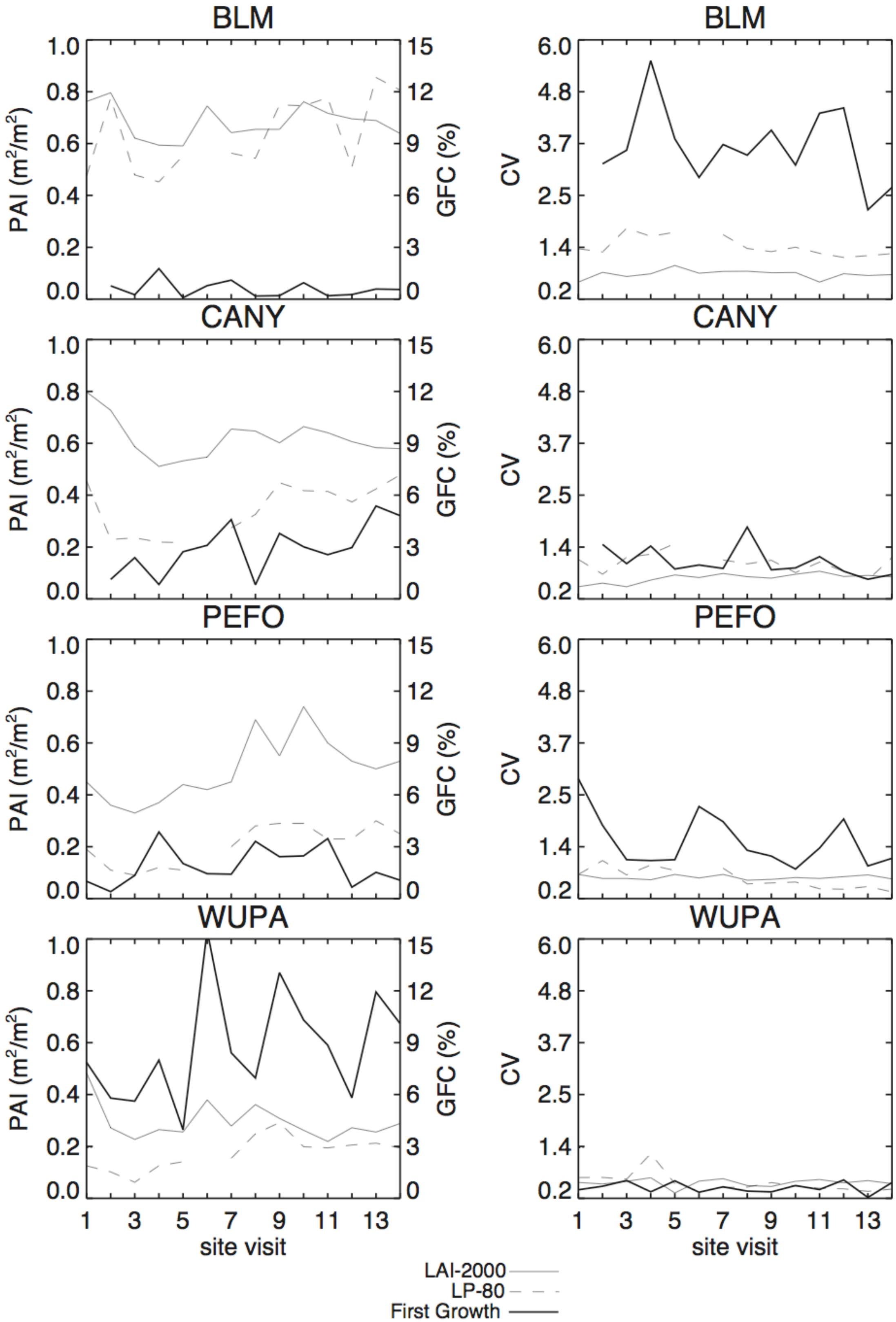
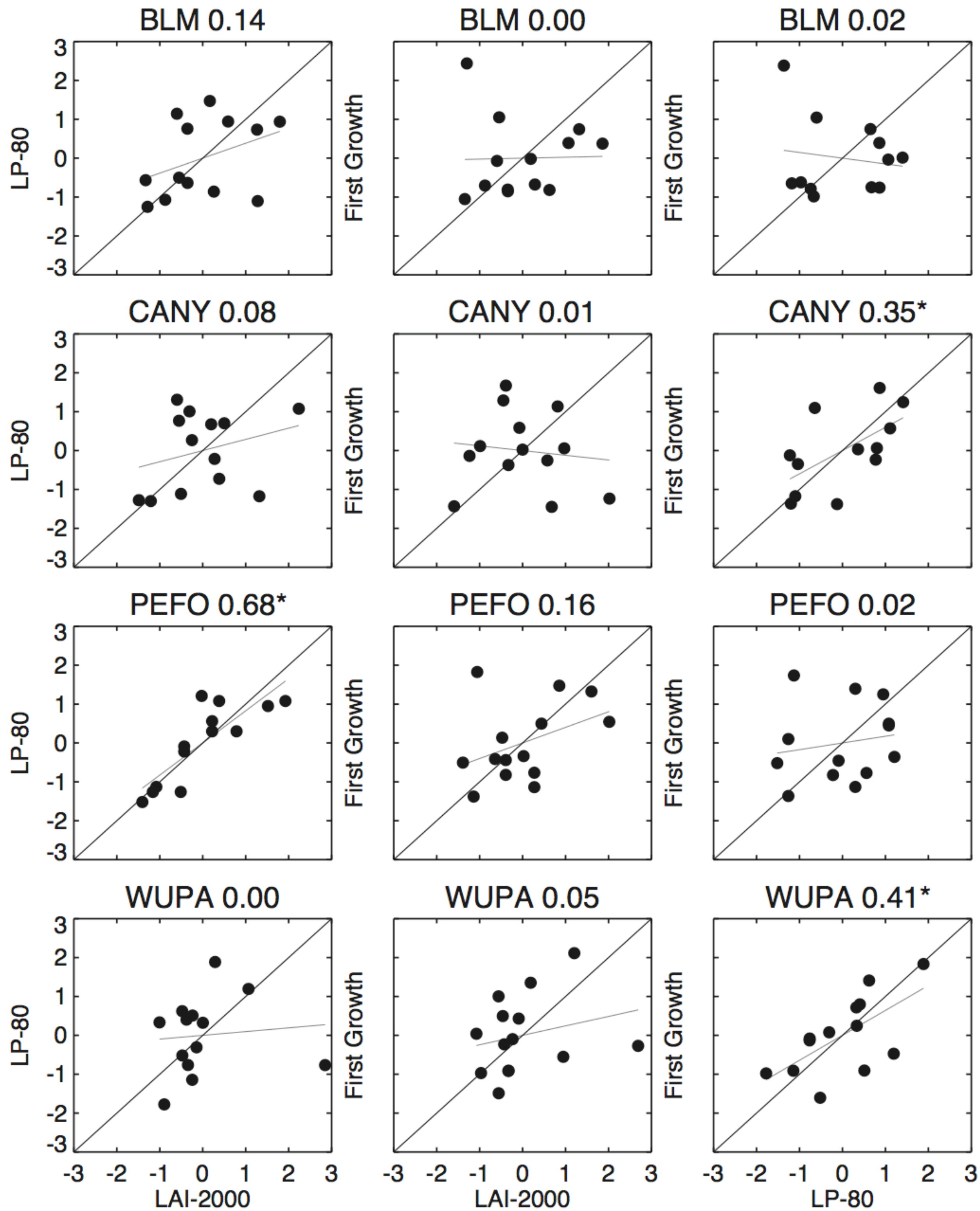

BLM
PAI (m²/m²)
GFC (%)
CV
CANY
PEFO
WUPA
site visit
LAI-2000
LP-80
First Growth

Figure 3



BLM 0.14
BLM 0.00
BLM 0.02
CANY 0.08
CANY 0.01
CANY 0.35*
PEFO 0.68*
PEFO 0.16
PEFO 0.02
WUPA 0.00
WUPA 0.05
WUPA 0.41*
LP-80
First Growth
LAI-2000
LP-80

Figure 4

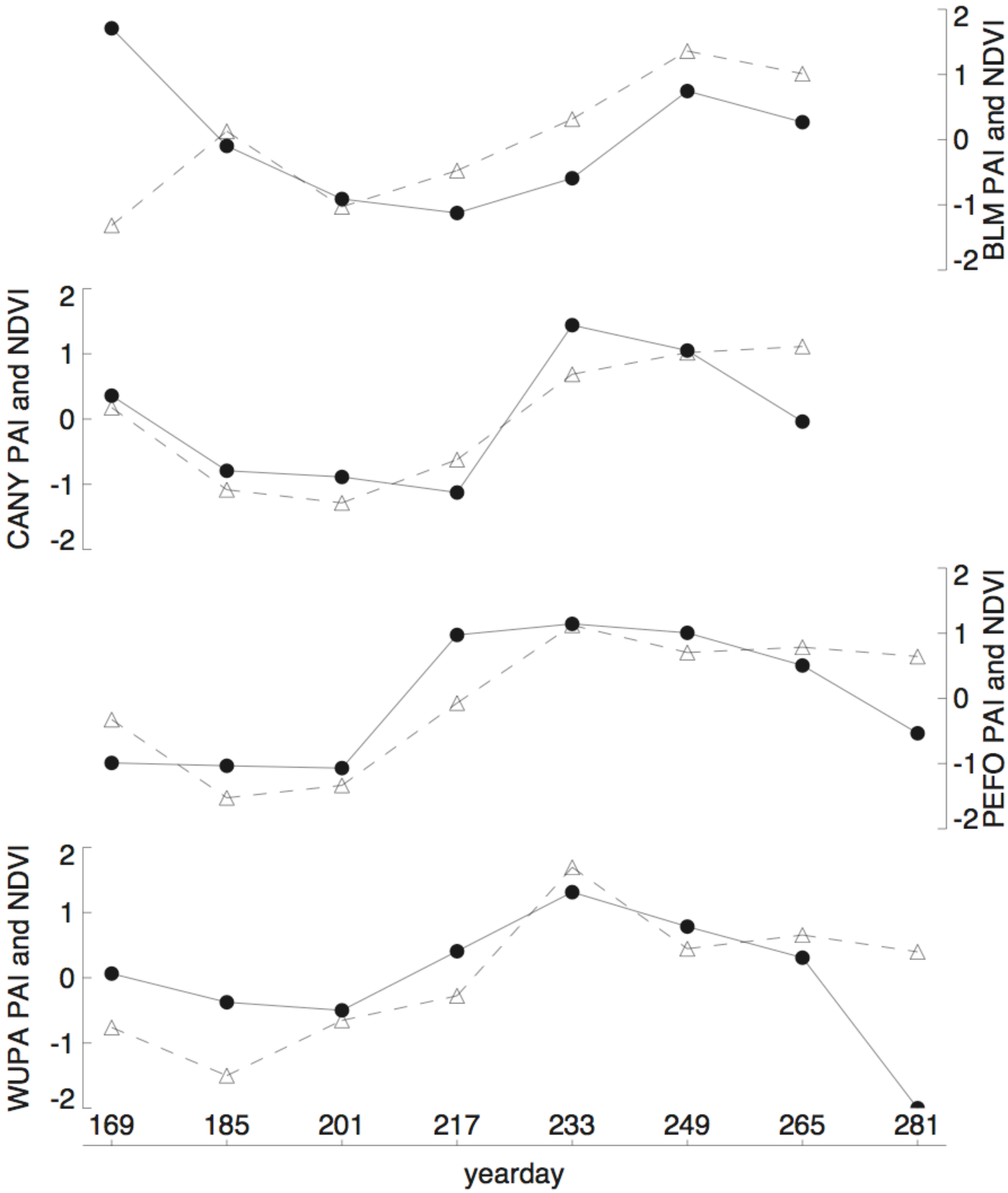
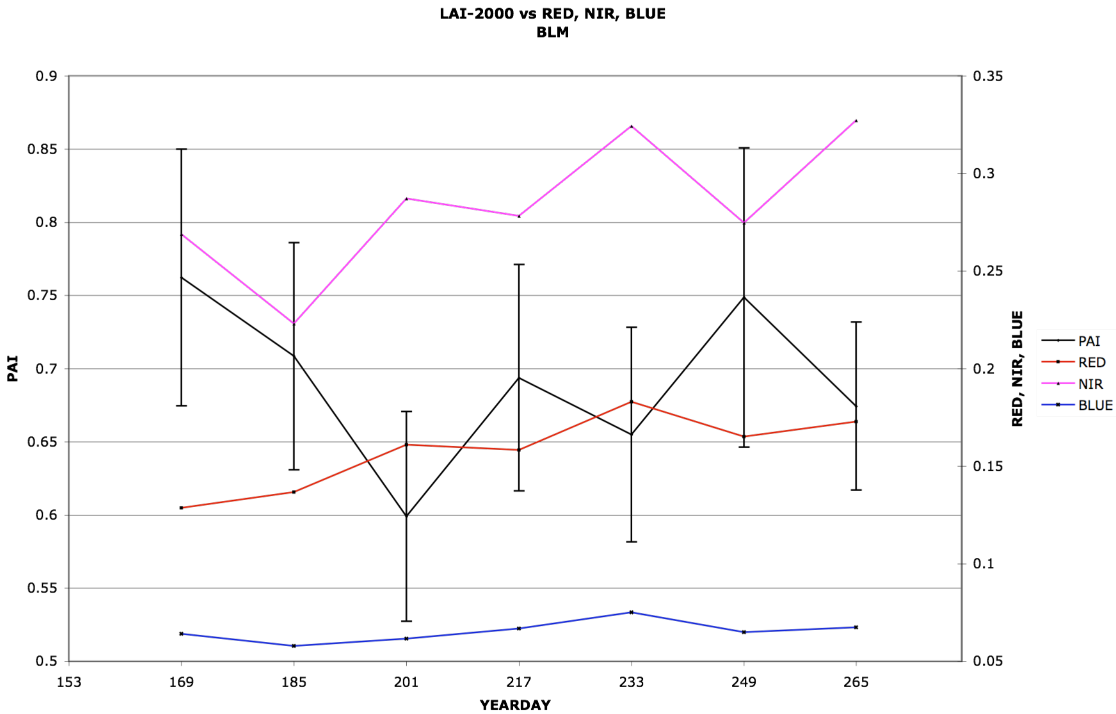

BLM PAI and NDVI
CANY PAI and NDVI
PEFO PAI and NDVI
WUPA PAI and NDVI
2
1
0
-1
-2
169
185
201
217
233
249
265
281
yearday

Figure 5

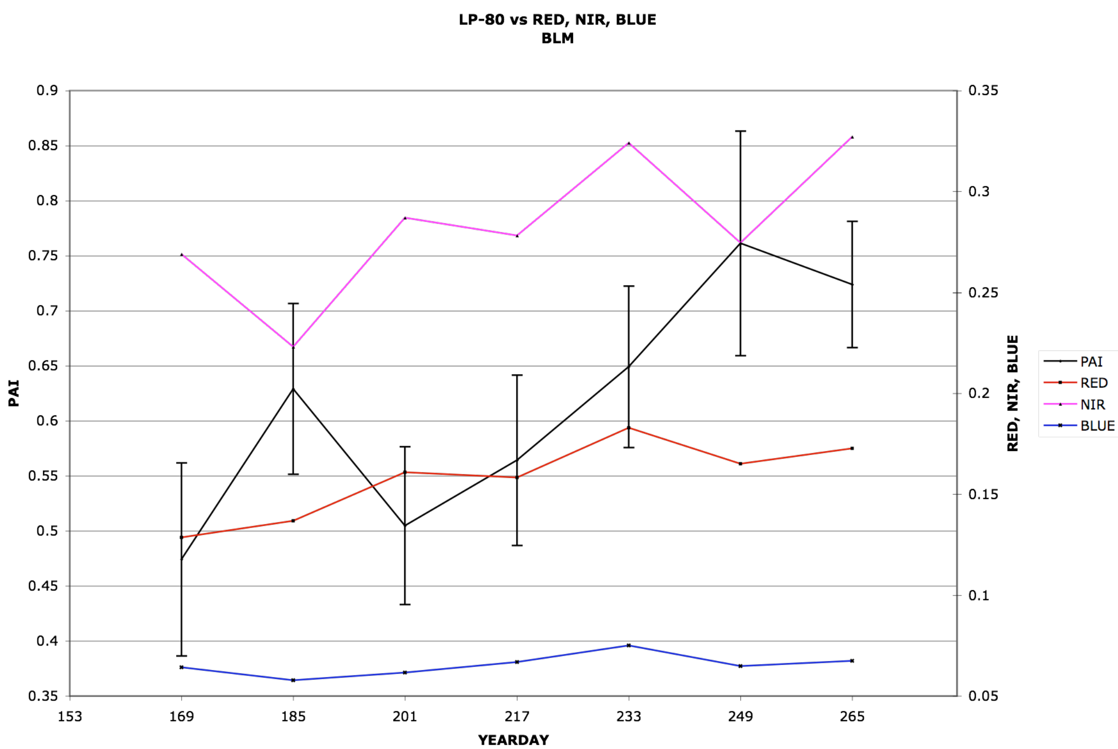
Appendix A. Qualitative Phenology.

This appendix shows patterns of PAI and GFC in relation to MODIS vegetation indices and channels (red, NIR, blue). There are 6 graphs per site organized as follows: (1) LAI-2000 versus EVI and NDVI; (2) LP-80 versus EVI and NDVI; (3) First Growth versus EVI and NDVI; (4) LAI-2000 versus channel data; (5) LP-80 versus channel data; and (6) First Growth versus channel data. Within each graph, presentation is organized such that visual separation of field data from MODIS data is maximized, i.e. we set axis ranges to customized values that are not consistent among graphs. In all cases, ground data is on the primary y-axis and MODIS data is on the secondary y-axis. Units are m^2/m^2 for PAI, percent for GFC (where 1.0 is 1%), dimensionless for EVI and NDVI, and percent for red, NIR, and blue (where 1.0 is 100%). Error bars show the 95% confidence interval.

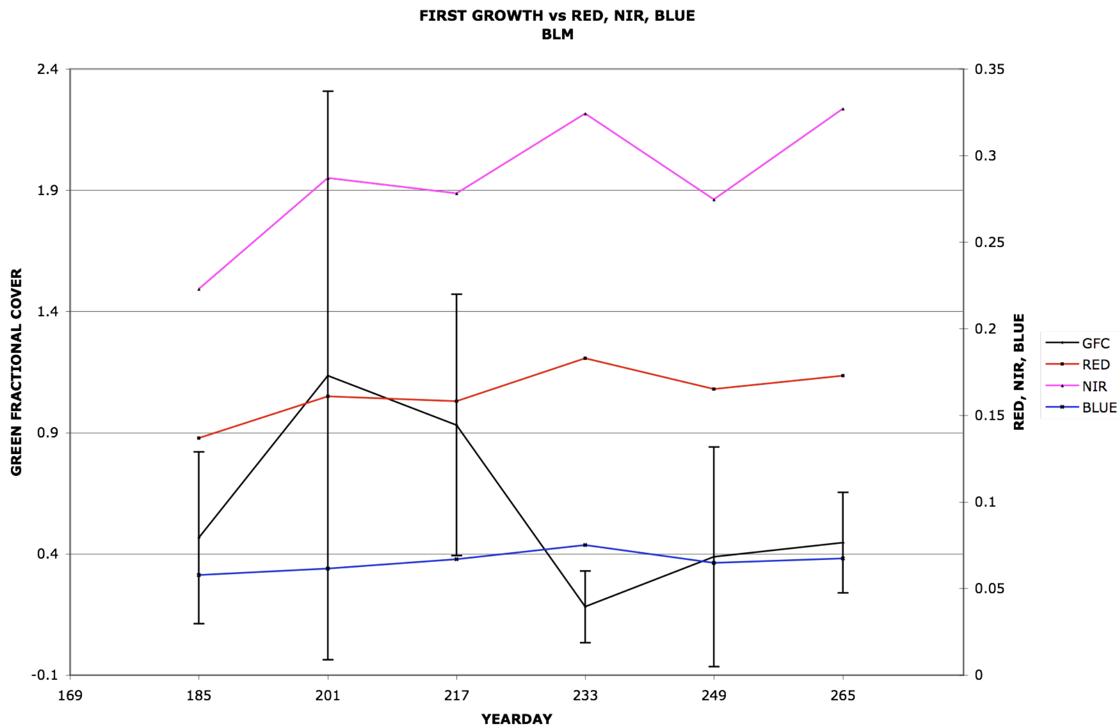
BLM

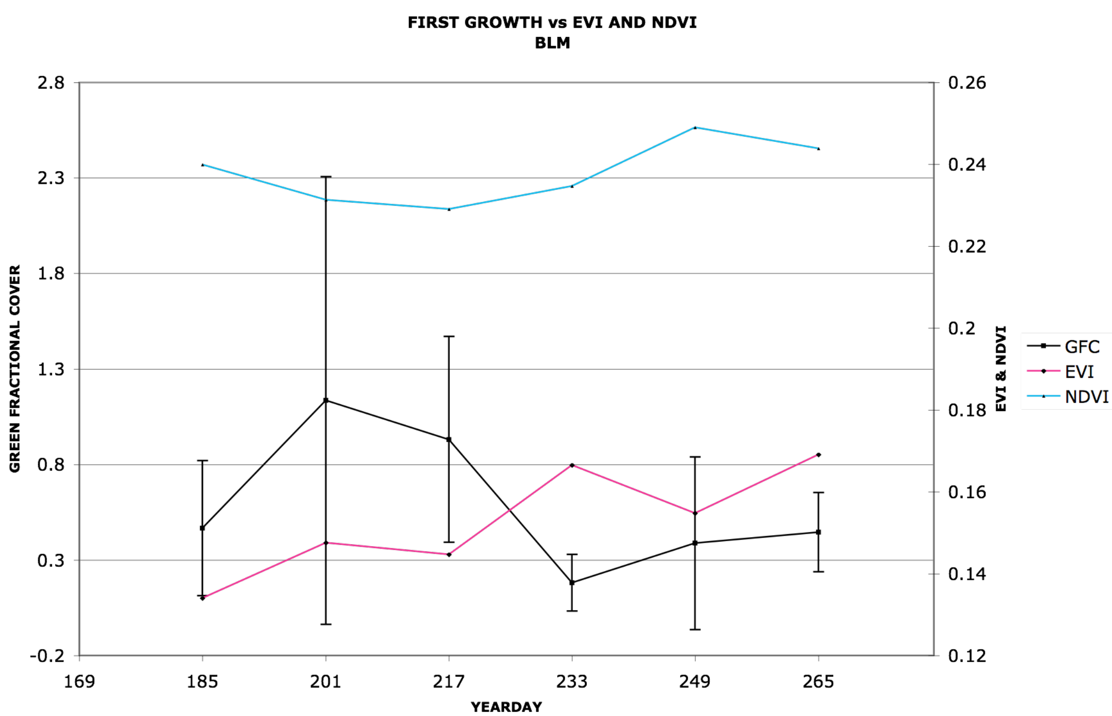


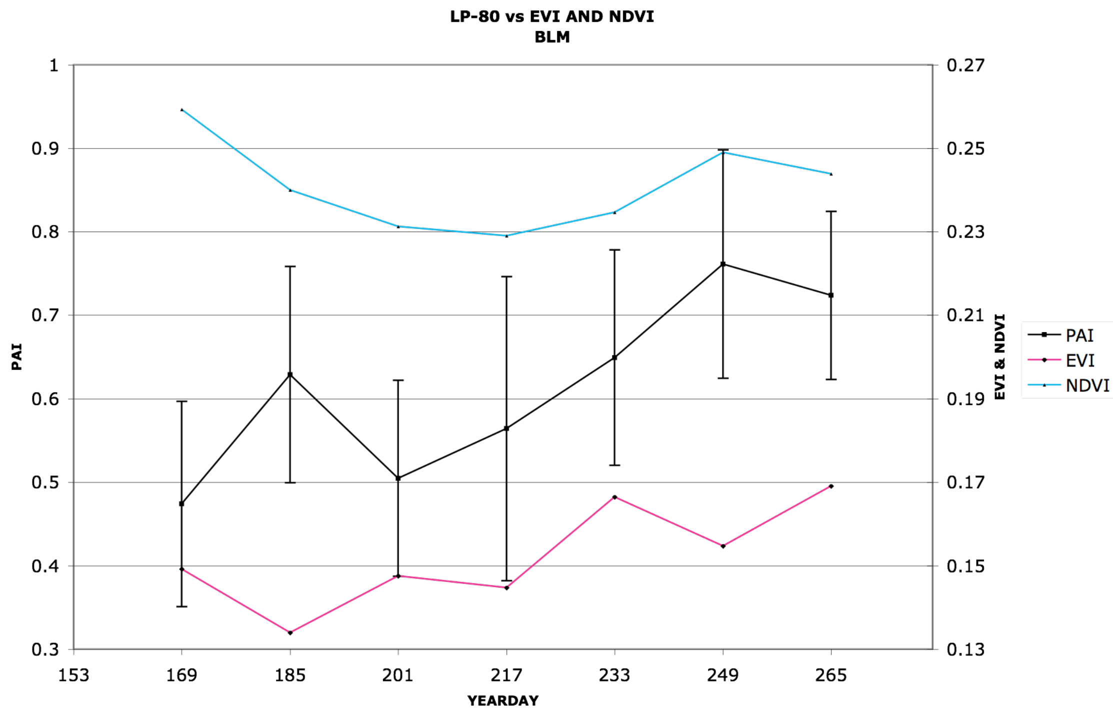
LAI-2000 vs RED, NIR, BLUE
BLM
PAI
RED, NIR, BLUE
YEARDAY
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.35
0.3
0.25
0.2
0.15
0.1
0.05
153
169
185
201
217
233
249
265
PAI
RED
NIR
BLUE

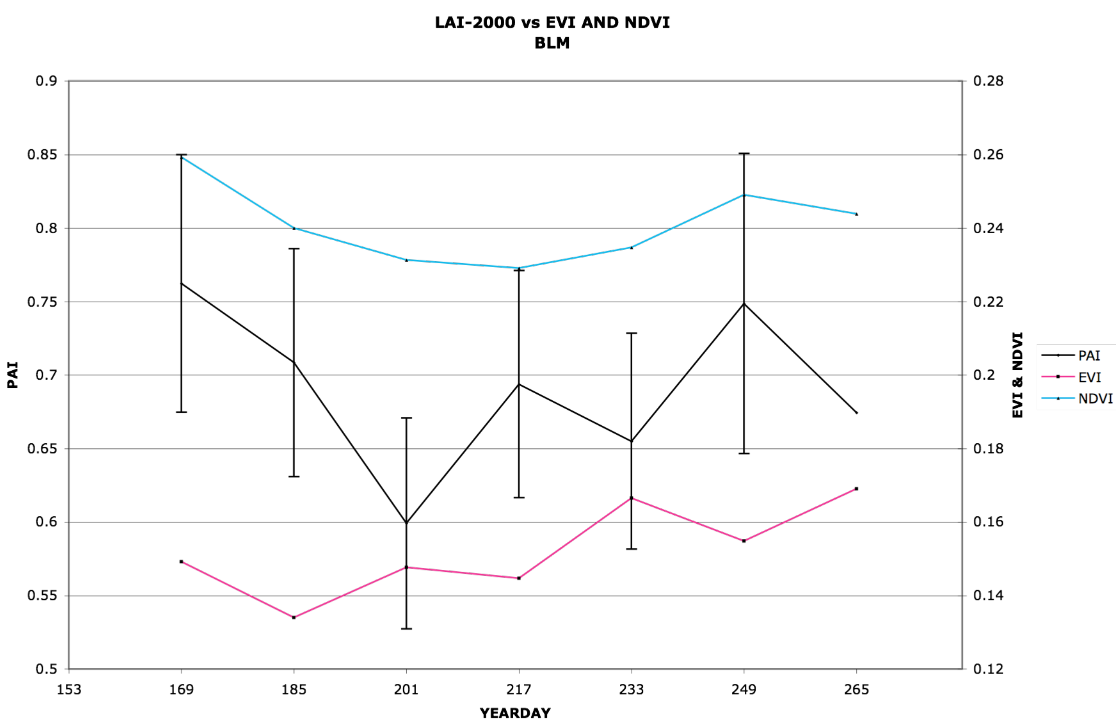


LP-80 vs RED, NIR, BLUE
BLM
PAI
RED, NIR, BLUE
YEARDAY
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.35
0.3
0.25
0.2
0.15
0.1
0.05
153
169
185
201
217
233
249
265
PAI
RED
NIR
BLUE

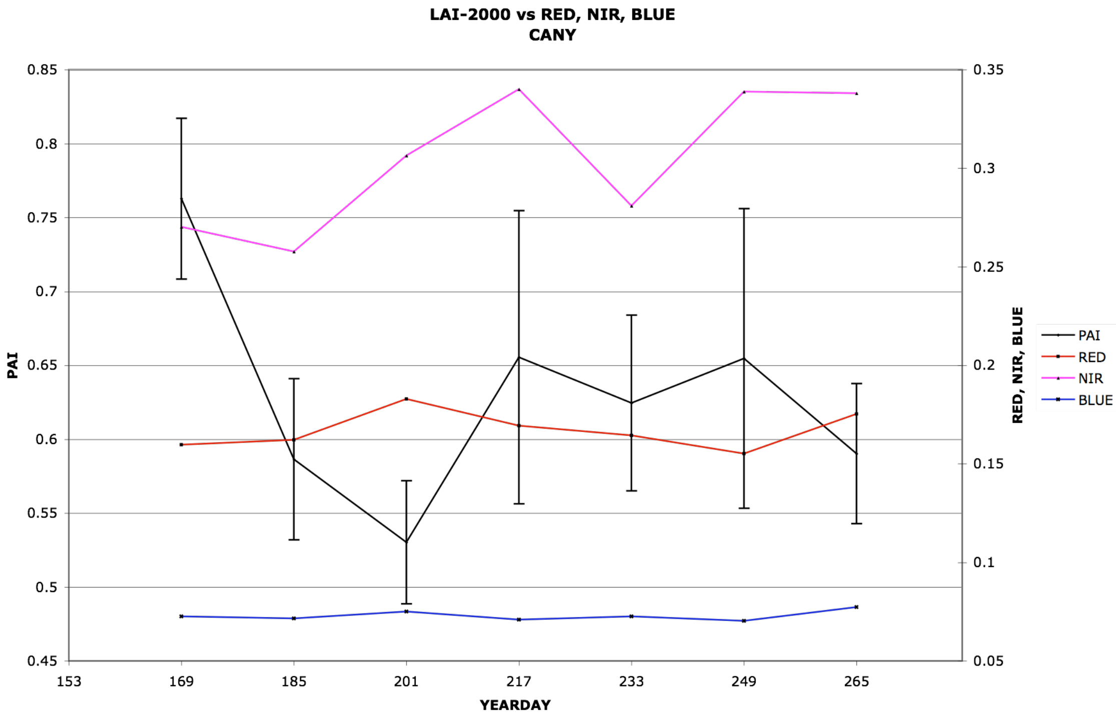

FIRST GROWTH vs RED, NIR, BLUE
BLM
GREEN FRACTIONAL COVER
RED, NIR, BLUE
YEARDAY
2.4
1.9
1.4
0.9
0.4
-0.1
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
169
185
201
217
233
249
265
GFC
RED
NIR
BLUE

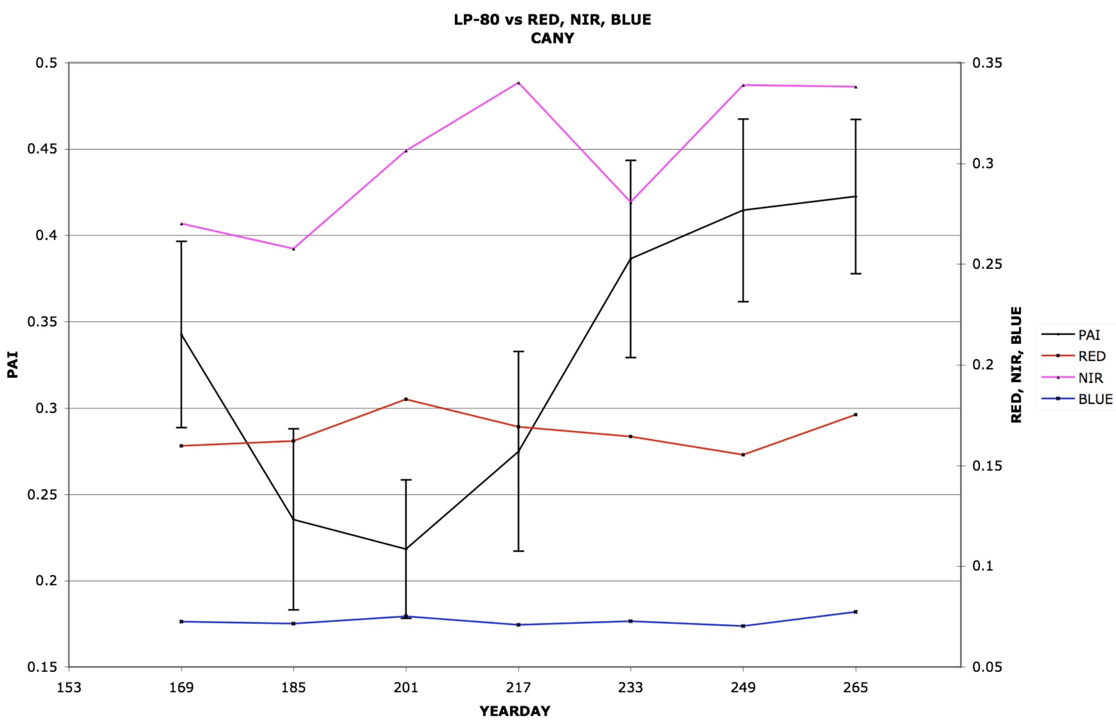

FIRST GROWTH vs EVI AND NDVI
BLM
GREEN FRACTIONAL COVER
EVI & NDVI
YEARDAY
2.8
2.3
1.8
1.3
0.8
0.3
-0.2
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
169
185
201
217
233
249
265
GFC
EVI
NDVI

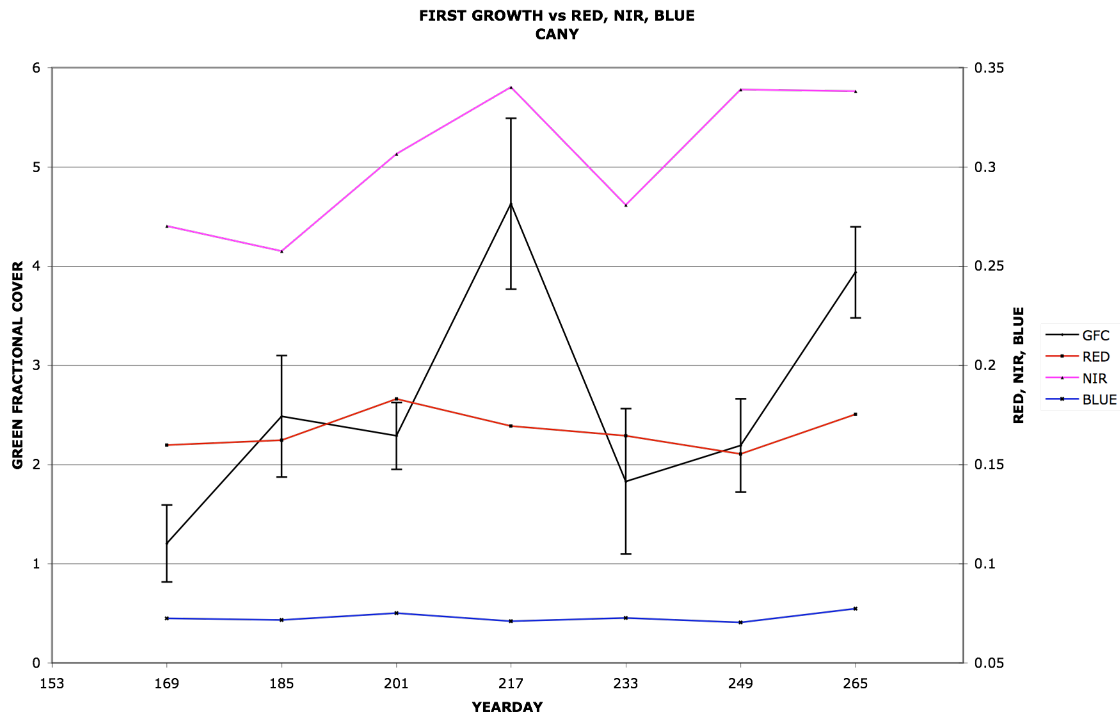

LP-80 vs EVI AND NDVI
BLM
PAI
EVI & NDVI
YEARDAY
PAI
EVI
NDVI
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.27
0.25
0.23
0.21
0.19
0.17
0.15
0.13
153
169
185
201
217
233
249
265


LAI-2000 vs EVI AND NDVI
BLM
PAI
EVI & NDVI
YEARDAY
PAI
EVI
NDVI
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
153
169
185
201
217
233
249
265

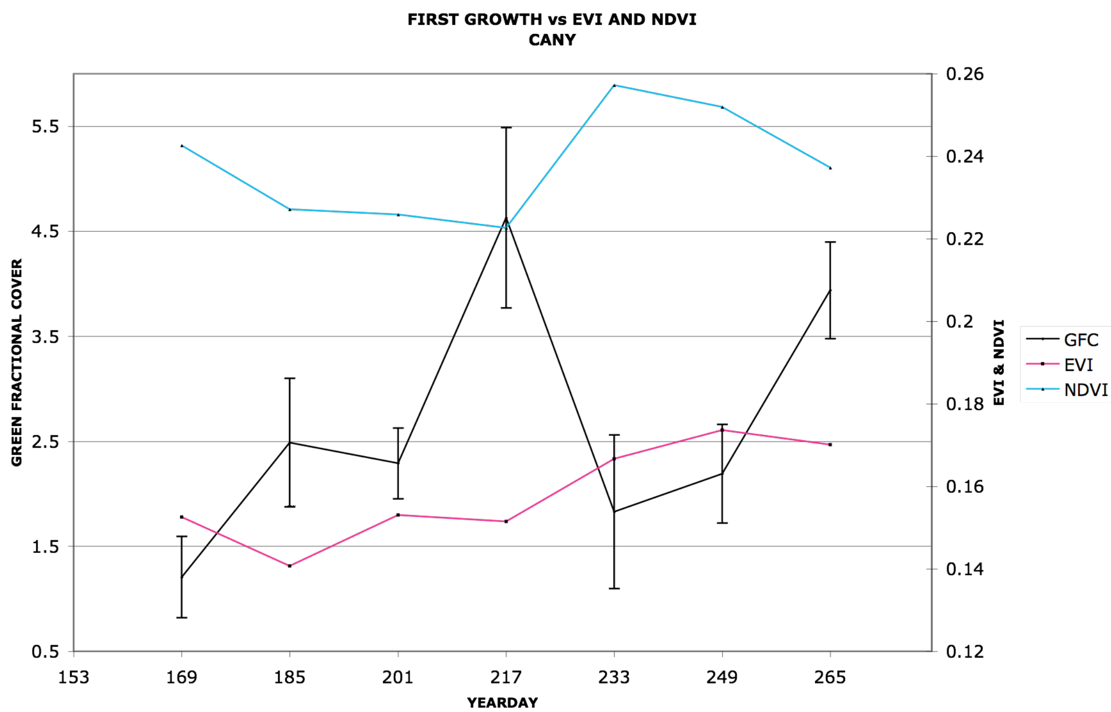
CANY


LAI-2000 vs RED, NIR, BLUE
CANY
PAI
RED, NIR, BLUE
YEARDAY
PAI
RED
NIR
BLUE

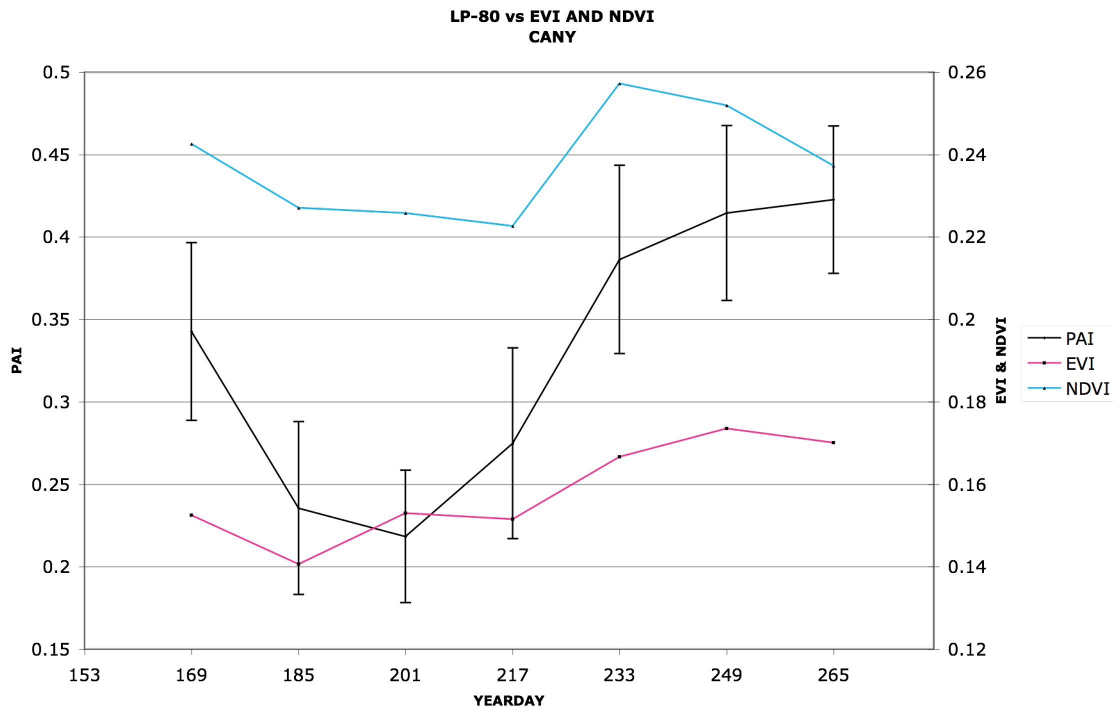

LP-80 vs RED, NIR, BLUE
CANY
PAI
RED, NIR, BLUE
YEARDAY
PAI
RED
NIR
BLUE

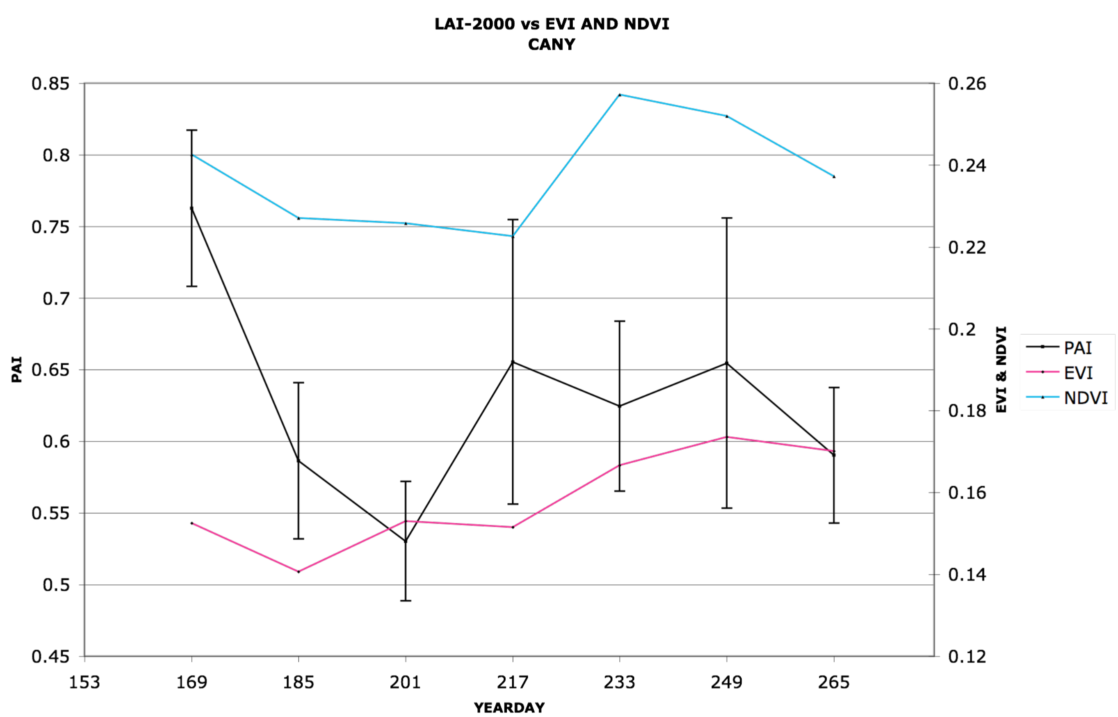


FIRST GROWTH vs RED, NIR, BLUE
CANY
GREEN FRACTIONAL COVER
RED, NIR, BLUE
YEARDAY
GFC
RED
NIR
BLUE
0
1
2
3
4
5
6
0.05
0.1
0.15
0.2
0.25
0.3
0.35
153
169
185
201
217
233
249
265

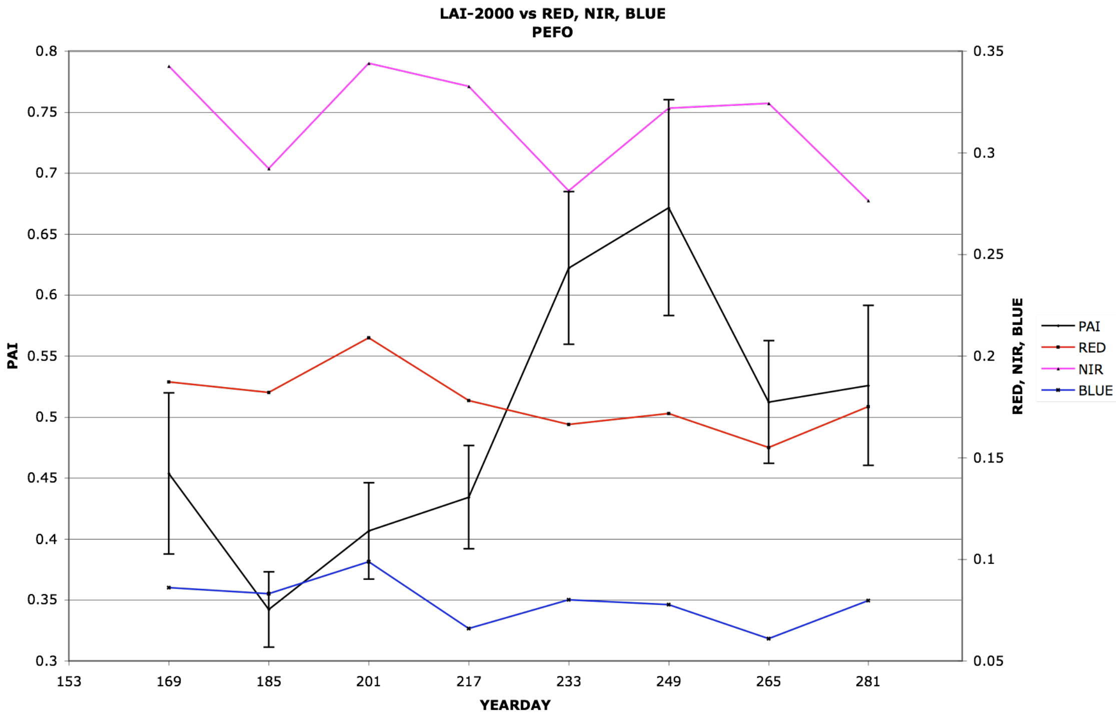


FIRST GROWTH vs EVI AND NDVI
CANY
GREEN FRACTIONAL COVER
EVI & NDVI
YEARDAY
GFC
EVI
NDVI
0.5
1.5
2.5
3.5
4.5
5.5
0.12
0.14
0.16
0.18
0.2
0.22
0.24
0.26
153
169
185
201
217
233
249
265

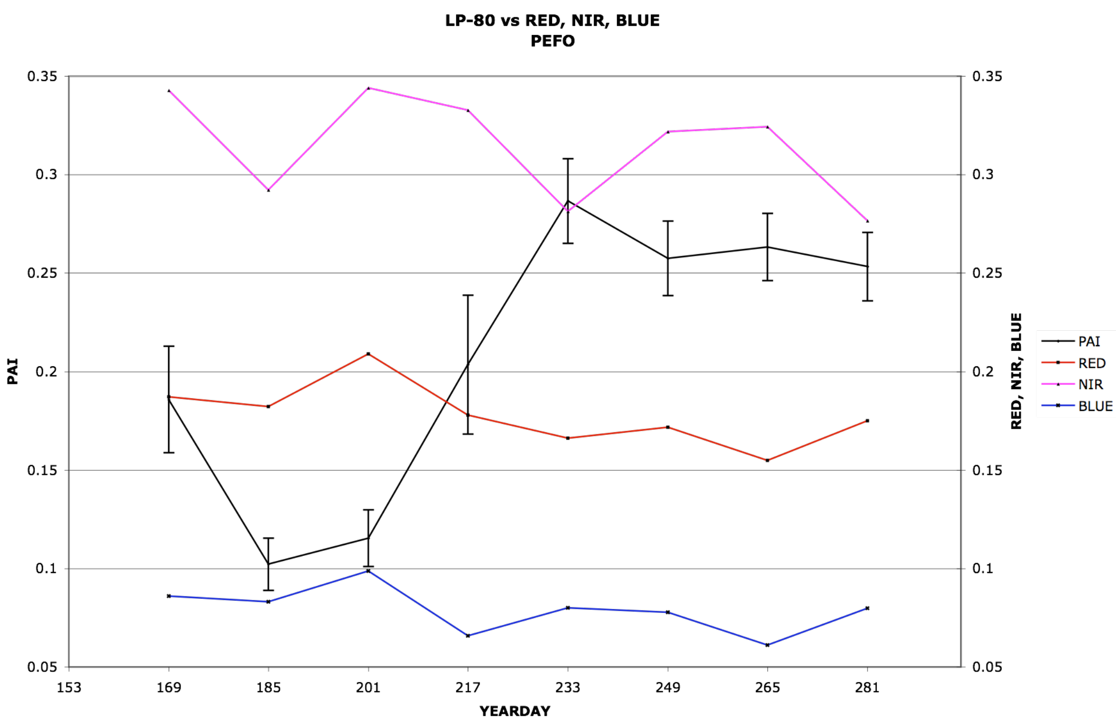

LP-80 vs EVI AND NDVI
CANY
PAI
EVI & NDVI
YEARDAY
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
153
169
185
201
217
233
249
265
PAI
EVI
NDVI


LAI-2000 vs EVI AND NDVI
CANY
PAI
EVI & NDVI
YEARDAY
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
153
169
185
201
217
233
249
265
PAI
EVI
NDVI

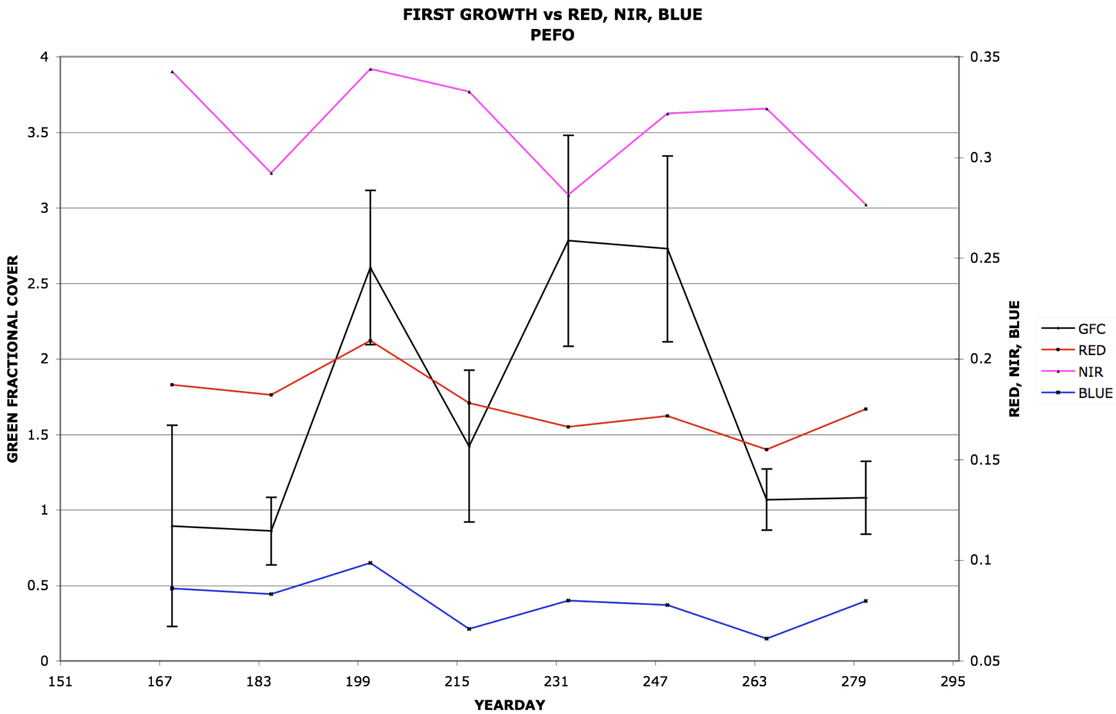
PEFO

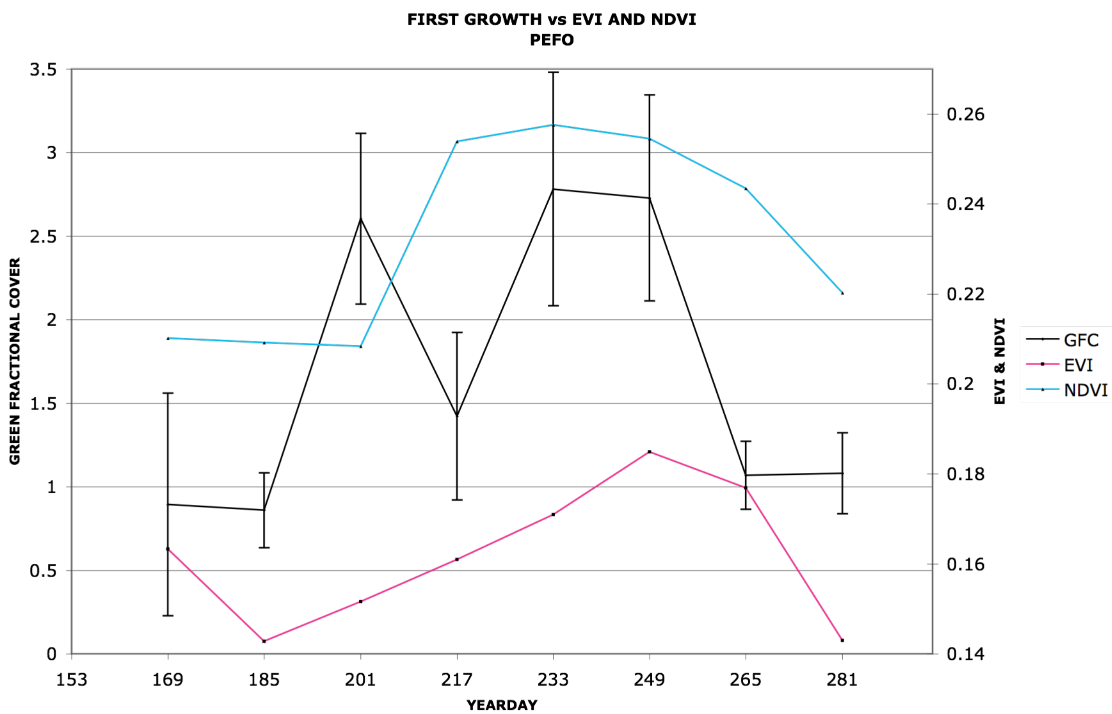


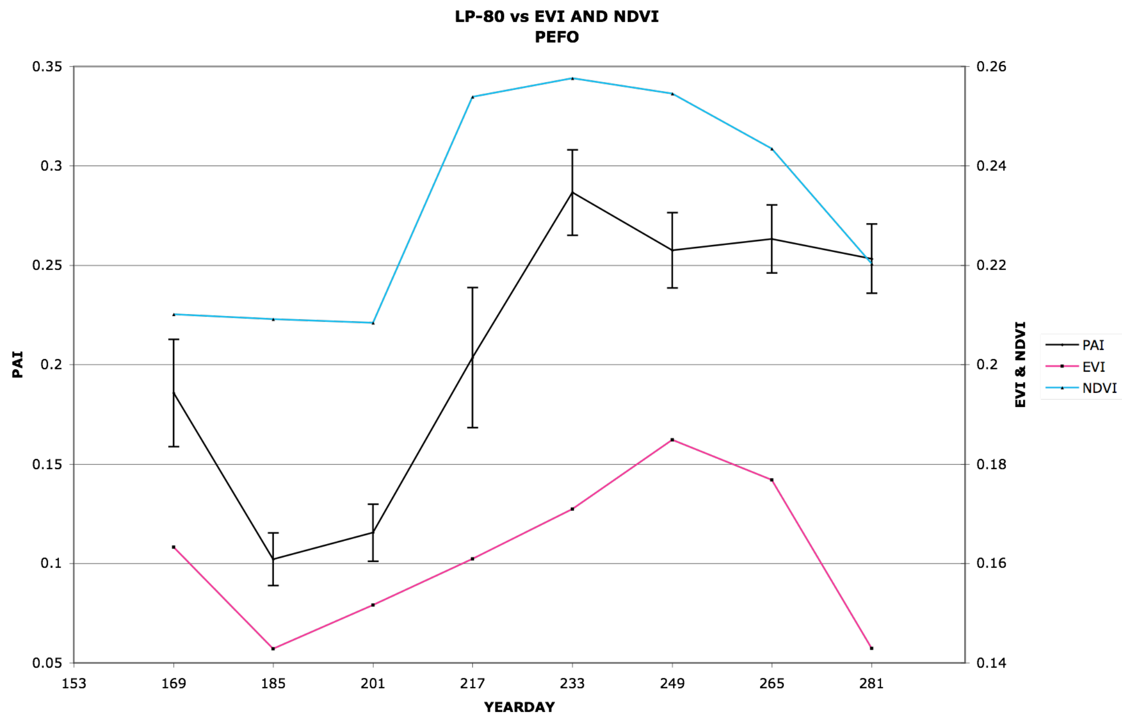
LAI-2000 vs RED, NIR, BLUE
PEFO
PAI
RED, NIR, BLUE
YEARDAY
PAI
RED
NIR
BLUE

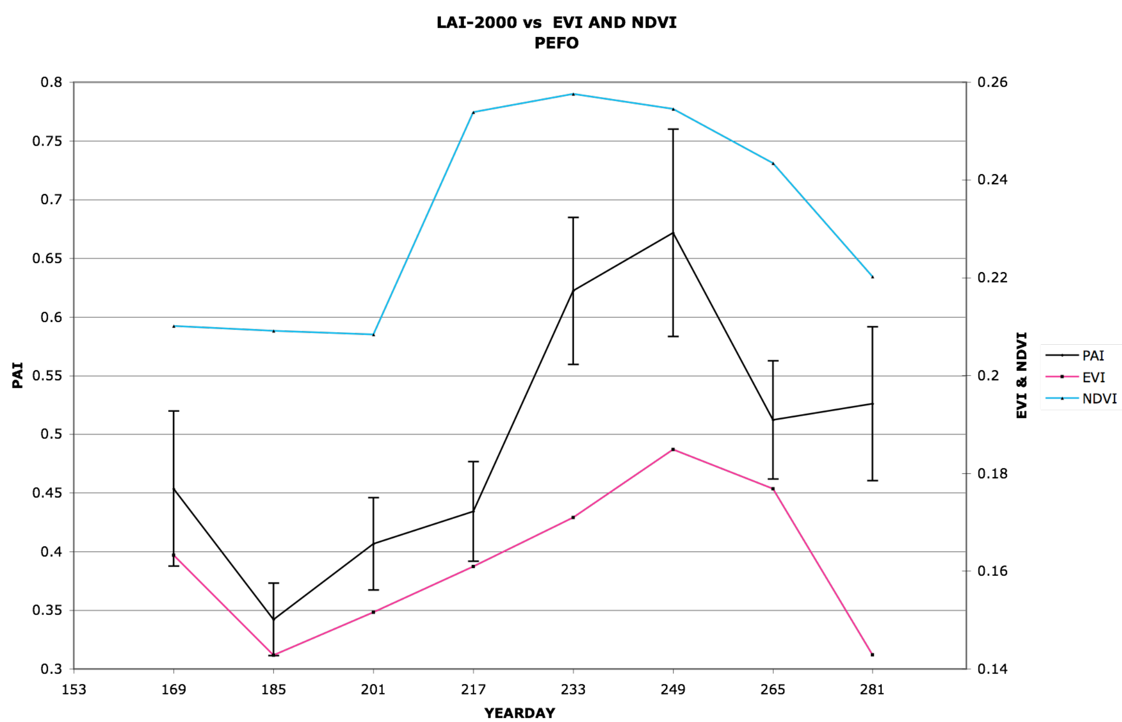


LP-80 vs RED, NIR, BLUE
PEFO
PAI
RED, NIR, BLUE
YEARDAY
PAI
RED
NIR
BLUE

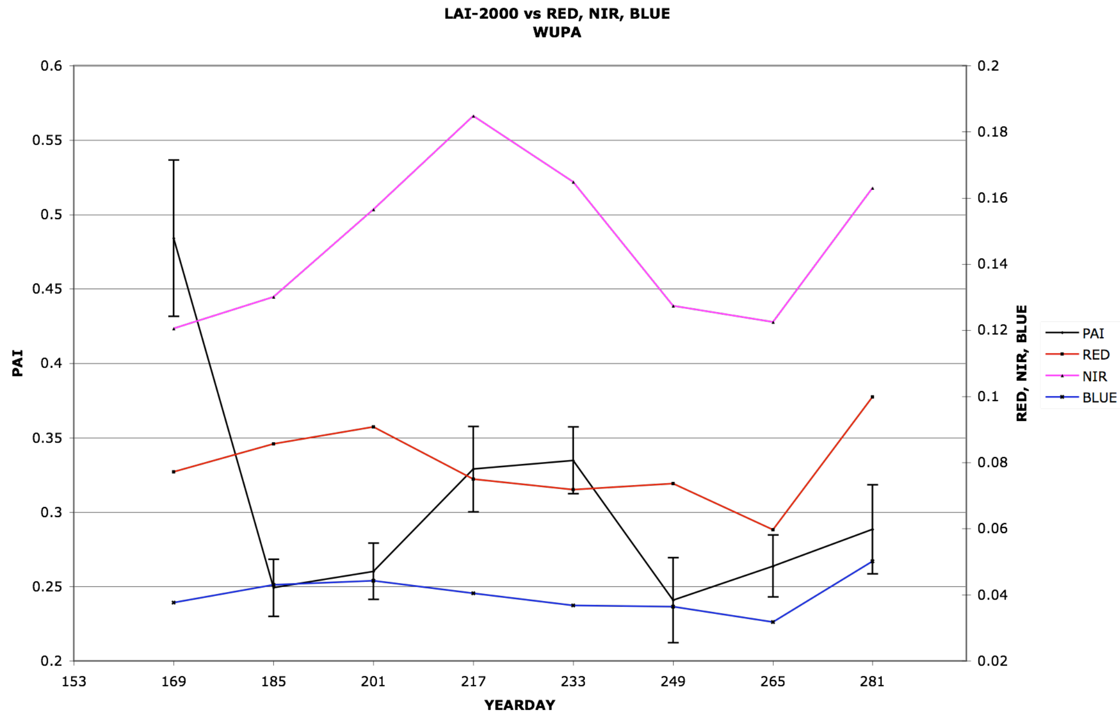

FIRST GROWTH vs RED, NIR, BLUE
PEFO
GREEN FRACTIONAL COVER
RED, NIR, BLUE
YEARDAY
GFC
RED
NIR
BLUE
4
3.5
3
2.5
2
1.5
1
0.5
0
0.35
0.3
0.25
0.2
0.15
0.1
0.05
151
167
183
199
215
231
247
263
279
295

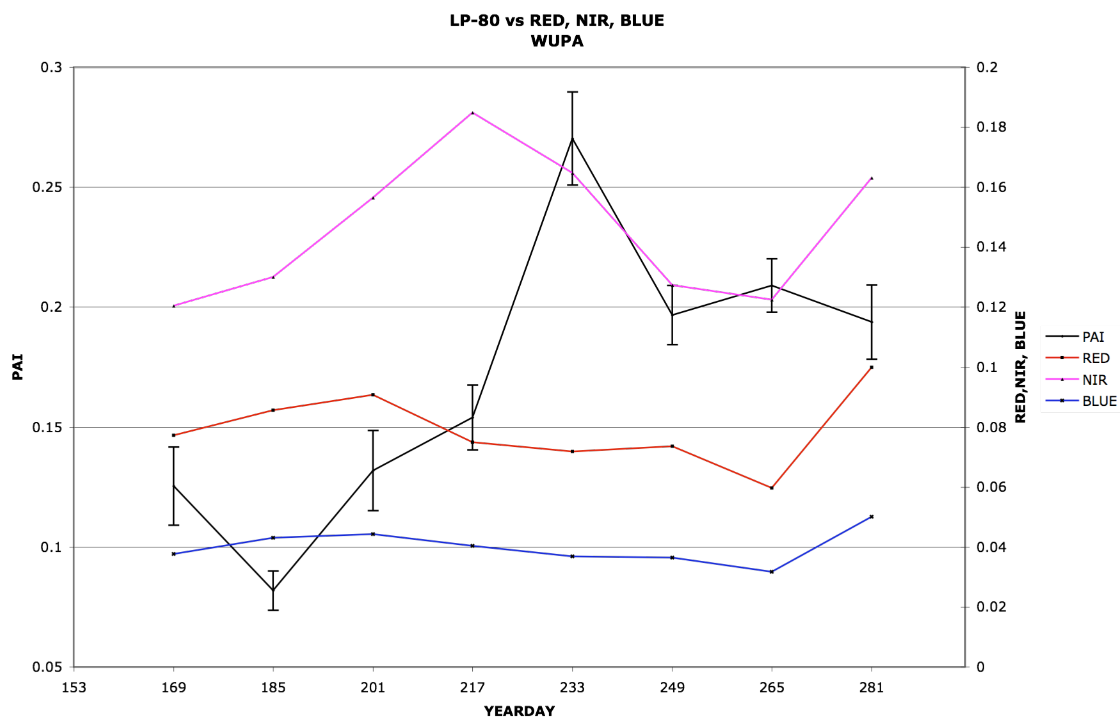

FIRST GROWTH vs EVI AND NDVI
PEFO
GREEN FRACTIONAL COVER
EVI & NDVI
YEARDAY
GFC
EVI
NDVI
3.5
3
2.5
2
1.5
1
0.5
0
0.26
0.24
0.22
0.2
0.18
0.16
0.14
153
169
185
201
217
233
249
265
281

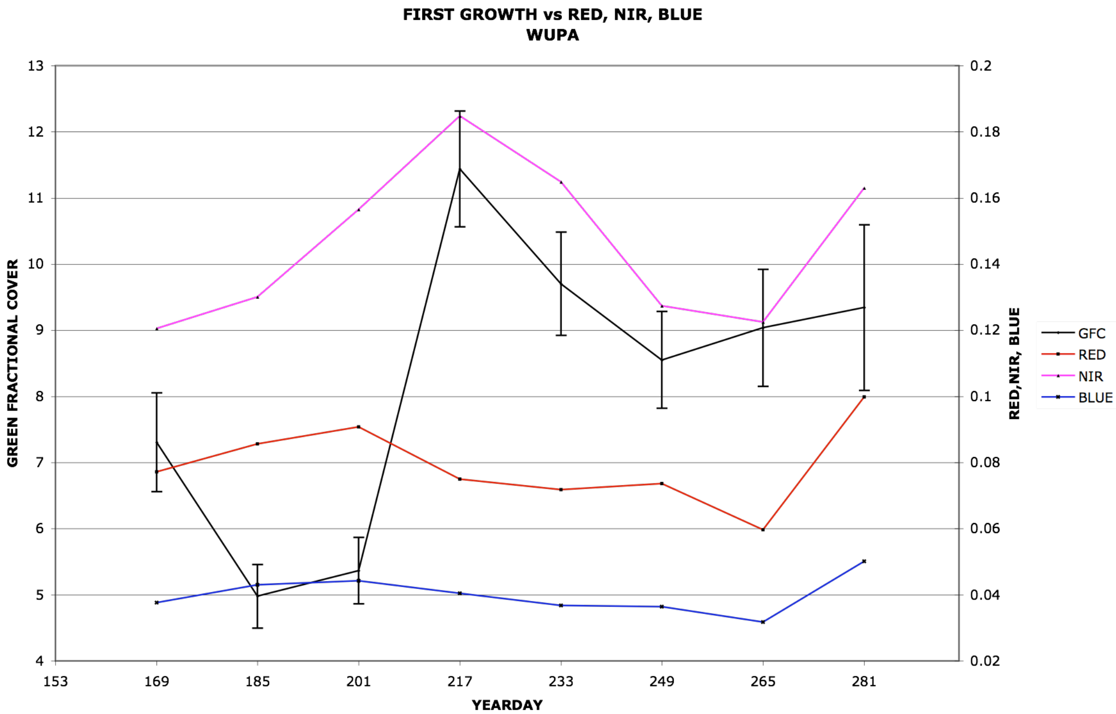

LP-80 vs EVI AND NDVI
PEFO
0.35
0.3
0.25
0.2
0.15
0.1
0.05
PAI
0.26
0.24
0.22
0.2
0.18
0.16
0.14
EVI & NDVI
153
169
185
201
217
233
249
265
281
YEARDAY
PAI
EVI
NDVI

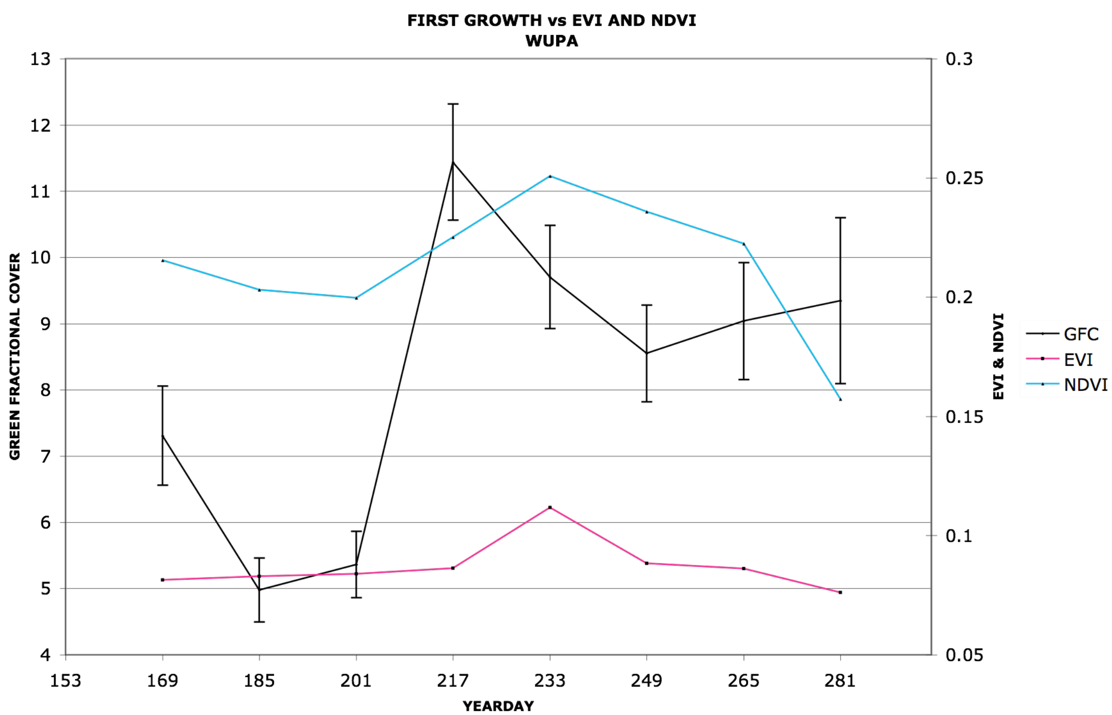

LAI-2000 vs EVI AND NDVI
PEFO
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
PAI
0.26
0.24
0.22
0.2
0.18
0.16
0.14
EVI & NDVI
153
169
185
201
217
233
249
265
281
YEARDAY
PAI
EVI
NDVI

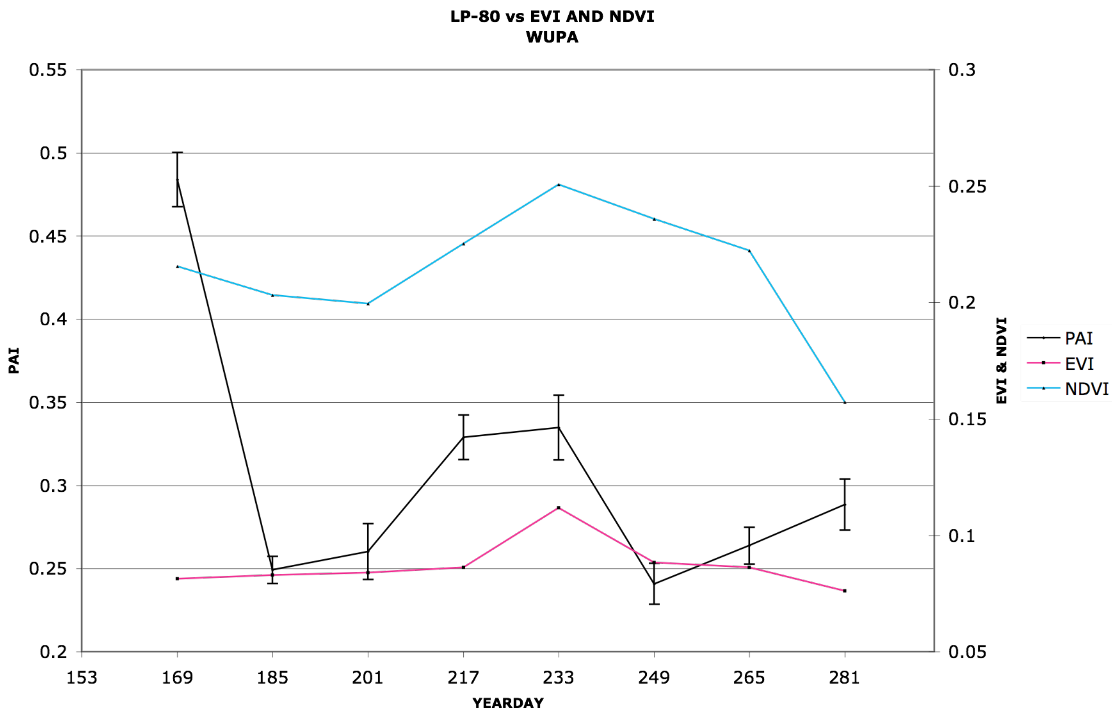
WUPA

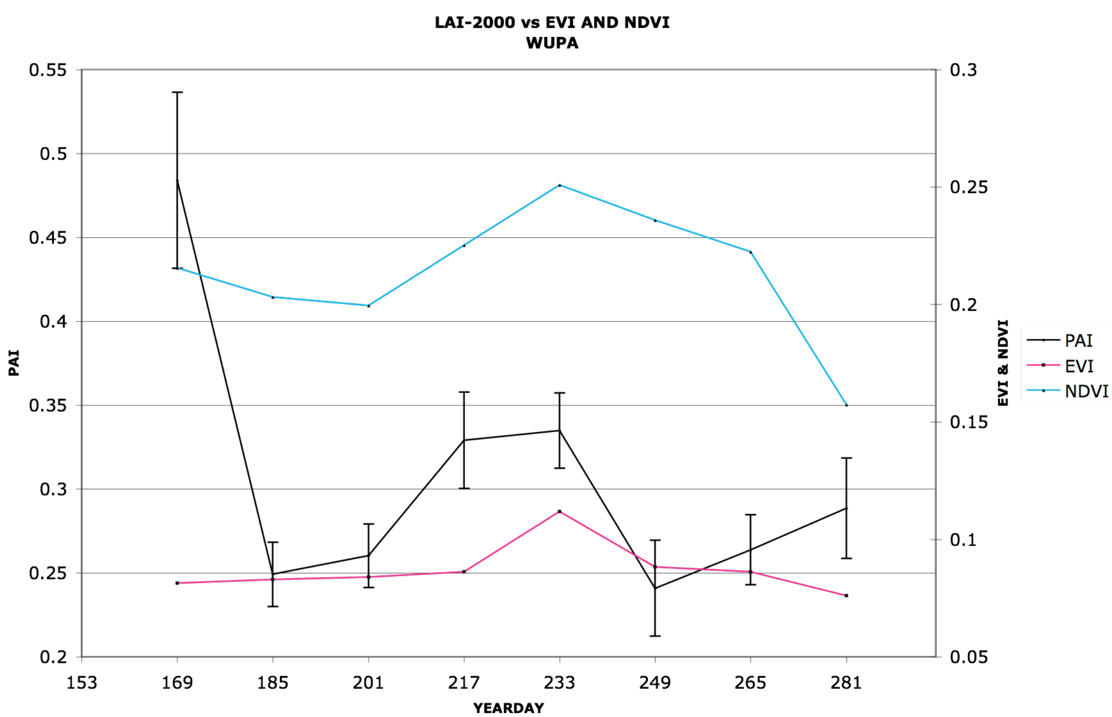

LAI-2000 vs RED, NIR, BLUE
WUPA
PAI
RED, NIR, BLUE
YEARDAY
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
153
169
185
201
217
233
249
265
281
PAI
RED
NIR
BLUE


LP-80 vs RED, NIR, BLUE
WUPA
PAI
RED,NIR, BLUE
YEARDAY
0.3
0.25
0.2
0.15
0.1
0.05
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
153
169
185
201
217
233
249
265
281
PAI
RED
NIR
BLUE


FIRST GROWTH vs RED, NIR, BLUE
WUPA
GREEN FRACTIONAL COVER
RED,NIR, BLUE
YEARDAY
GFC
RED
NIR
BLUE
13
12
11
10
9
8
7
6
5
4
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
153
169
185
201
217
233
249
265
281


FIRST GROWTH vs EVI AND NDVI
WUPA
GREEN FRACTIONAL COVER
EVI & NDVI
YEARDAY
GFC
EVI
NDVI
13
12
11
10
9
8
7
6
5
4
0.3
0.25
0.2
0.15
0.1
0.05
153
169
185
201
217
233
249
265
281


LP-80 vs EVI AND NDVI
WUPA
PAI
EVI & NDVI
YEARDAY
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.3
0.25
0.2
0.15
0.1
0.05
153
169
185
201
217
233
249
265
281
PAI
EVI
NDVI


LAI-2000 vs EVI AND NDVI
WUPA
PAI
EVI & NDVI
YEARDAY
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.3
0.25
0.2
0.15
0.1
0.05
153
169
185
201
217
233
249
265
281
PAI
EVI
NDVI