Biogeosciences Discuss., 11, C1757–C1774, 2014
www.biogeosciences-discuss.net/11/C1757/2014/

Biogeosciences
Discussions
Open Access

Interactive comment on “Evaluating remote sensing of deciduous forest phenology at multiple spatial scales using PhenoCam imagery” *by* S. T. Klosterman et al.

S. T. Klosterman et al.

klosterman@fas.harvard.edu

Received and published: 22 May 2014

The authors wish to thank the two anonymous reviewers for their thorough and insightful comments. We believe that through addressing these comments, the manuscript will be greatly improved. We respond to both reviews here, organized by individual comment:

======= =======

Review 1

======= “P2307 L10 Please mention the background information about PhenoCam network.”

We add to P2309 L6:

>The PhenoCam network is a continental-scale phenological observatory, spanning a wide range of biogeoclimatic zones and vegetation types, primarily in the United States. In addition to retrieving imagery from publicly available webcams with either hourly or half-hourly temporal resolution, the network consists of 85 cameras deployed following a standardized protocol, which upload half-hourly imagery to the PhenoCam server from 4 am to 10 pm each day. Imagery and data products are available at the PhenoCam web page: http://phenocam.sr.unh.edu/webcam/.

======= “P2309 L21 How large was the analyzed canopy cover area? How many photo images were captured during the day? Authors should add the basic information related to the data collection and data quality.”

To address these questions, we add to P2310 L1:

>ROIs contained approximately 10-100 trees depending on the site.

P2309 L6 is amended as described in the previous comment response to clarify image temporal resolution and number of images per day.

======= “P2310 L7 I want to know how to define the “site-dependent threshold”. If the authors can propose the general method of data filtering, it will be valuable for the readers.”

We insert the following at P2310 L7 to clarify this point:

>We recorded images at some sites from before sunrise until after sunset. As shown by Sonnentag et al. (2012), images recorded at dawn and dusk, under very low levels of diffuse illumination and with no direct solar beam, tended to have much lower GCC values than those recorded at mid-day. We therefore excluded extremely dark images (sample image shown below, Figure 1 of comment response) from further con-

sideration. Due to varying camera characteristics from site to site (e.g. color balance, maximum exposure time, automatic gain control, internal image processing, etc.), it was necessary to vary the threshold across sites.

We based our method for determining the brightness thresholds using histograms of ROI total brightness, as shown below (Figure 2 of comment response) for one year of data from Harvard Forest. The distribution is bimodal, because there are a large number of images taken before sunup or after sunrise.

Our method essentially selected a brightness threshold between the two peaks of the distribution, such that only the darkest images were excluded.

======= “P2311 L1 Did authors test the satellite GCC? I can understand the reason why they analyze EVI and NDVI, since these VIs are main parameters of common satellite products. However, if the authors want to argue the effect of landscape metric on the accuracy of phenology estimation, the same VI should be compared between satellite and near-surface sensors to minimize the effects of different wavebands.”

We add to P2311 L13 to address this comment:

>We also analyzed GCC time series from remote sensing, calculated according to Equation 1. Remote sensing GCC time series suffered from lower quality than EVI and NDVI, with more noise and outliers even after applying the quality control procedures used on those time series. The lower quality of MODIS GCC time series caused relatively high statistical uncertainty in estimated phenophase transition dates. For example, the average statistical uncertainty (95% confidence interval) for phenophase transition dates identified from MODIS GCC time series using the generalized sigmoid method, described below, was 17 days, twice as large as that of EVI time series. Because of this uncertainty, we do not report MODIS GCC results here. However, we note that Hufkens et al. (2012) used remote sensing data to calculate phenology dates with the excess greenness index, a spectral index similar to GCC, and obtained similar results to NDVI, an index used in this study.

======= “P2320 L11-L20 This explanation about the time lag between maturity date ($\approx$ max. LMA, LAI) and GCC-derived date is very interesting. Can we solve this problem by using other wavebands related to leaf mass (NIR), water absorption and/or secondary metabolites (SWIR)?”

Observers generally identified leaf maturity after the peak of GCC from tower-mounted cameras; the observers associated a dark green canopy with maturity, whereas peak GCC corresponded to a bright yellow canopy. Keenan et al (in press) note that camera GCC is determined by a combination of leaf area index and leaf color, with changes in leaf color causing the decline in GCC from its early season peak. It is not clear how information from other wavebands, such as NIR and SWIR, would inform the difference between peak GCC, derived from visible bands, and observer assessments also based on visible light. In future work however, we plan to explore how direct assessments of organisms, as opposed to assessments of digital images of organisms, relate to near surface remote sensing of canopy phenology, which may help solve this problem.

We revise P2320 L11-L20 to clarify the description of peak GCC:

>The visually assessed date of leaf maturity was later than the end of spring date derived from near-surface GCC. At visually assessed maturity, leaves were darker green, whereas at the GCC-derived end of spring date, leaves were bright yellow-green. The shift from brighter to darker green was associated with an increase in the relative brightness of the blue channel.

>A recent study explored possible reasons for this, finding that GCC from tower mounted cameras reached its spring time maximum about two weeks before a suite of leaf and canopy physiological traits including chlorophyll fluorescence, leaf area and mass, nitrogen, carbon, water content, and leaf area index (Keenan et al., in press). That study concluded that GCC reaches its peak as the effective LAI viewed from tower-mounted cameras saturates, and GCC becomes insensitive to further increases in LAI, but begins to decrease due to changes in leaf color.

======= “P2320 L23-L26 Hmimina et al. (2013) have not analyzed the difference between VIS band indices and VIS-NIR indices. Can we ignore the difference of VI really?”

We expand and clarify discussion of spectral differences by revising P2320 L23-28 as follows:

>Different spectral indices exhibit different temporal trajectories (Yang et al., 2014), and have been reported to correlate with different plant traits. Hufkens et al (2012) noted that both the excess green index, a color index similar to the GCC used in this study, and NDVI tended to saturate before EVI, with insensitivity to later changes in LAI. This effect may result in biases due to spectral difference. However a recent study also noted that both EVI from remote sensing and GCC from tower mounted cameras reach their maximum values about two weeks before a suite of leaf and canopy physiological traits (Keenan et al., in press). Recent work indicates that a bias between end of spring phenology at the near surface and remote sensing scales may not be due to spectral difference: Hmimina et al. (2013) found a similar late spring bias using NDVI from remote sensing and near-surface NDVI sensors.

>Camera fields of view are smaller than ground areas associated with satellite pixels. Consequently, GCC from cameras can only be expected to agree with satellite vegetation indices to the extent that the camera field of view represents the vegetation in the satellite pixel. We conduct a land cover analysis to explore the nature of the end of spring bias found in this study (Fig. 6), finding a relationship between landscape composition of satellite observation areas and the length of the late spring bias.

P2320 L28 – P2321 L9 and the revision to P2322 L5-L10 proposed below continue this discussion.

======= “P2320 L28-P2321 L9 If this relationship was found only in late spring, please let me know the reason why. I guess that the difference of fractional forest cover may cause bias also in other phenological stages.”

To address this comment, we add the following at P2321 L2

>For the other phenological transitions (SOS, MOS, SOF, MOF, and EOF), the statistical relationship of the bias between remote sensing and near-surface phenology, to fractional forest cover, was not significant ($p > 0.05$). This indicates that whatever the mechanistic explanation for the correlation between late spring bias and fractional forest cover might be, it would likely not apply to other seasonal transitions.

Recommendations for additional observations that could inform the cause of the bias are given on P2321 L5-9, specifically to photograph larger areas, capturing more plants and plant functional types, using multiple cameras, and analyzing images with multiple regions of interest.

======= “P2321 L20-P2322 L4 This discussion is acceptable. On the other hand, the evaluation of heterogeneity of phenology is important to understand the diversity of ecological function and its response to environmental stresses, and we can monitor it by using near-surface camera having high temporal/spatial resolution.”

We agree with this comment. We have already enthusiastically recommended this kind of monitoring on P2322 L5-L10, and propose the following expansion on this section:

>To more accurately study spatial variation in autumn phenology, and to further study the late spring bias in heterogeneous forested landscapes reported above, photography of larger fields of view, and more plants and plant functional types, should be obtained (Hufkens et al., 2012). Use of multiple cameras at a single site, and multiple regions of interest on a given image (Richardson et al., 2009), could inform the use of mixing models for combining phenological information from diverse plant functional types. Direct visual assessment of organisms, representing the range of ecological diversity at study sites, should complement these measurements to provide biological interpretation of digital camera metrics.

======= “P2330 Table 1 If possible, please add the information about dominant species and maximum LAI. The estiamtaion accuracy would be affected by species-difference, tree density and leaf mass."

Species and LAI information are not available at all sites, since many sites are not research forests, but have digital cameras nonetheless. Therefore, to characterize land cover, the authors used analysis of high resolution remote sensing data, shown in Table 1.

======= "P2332 Table 3 Why is not MOS shown?"

The end of spring (EOS) date from the curve fitting analysis matched the visually assessed date of canopy maturity more closely than the middle of spring (MOS) date, so only results using the EOS date are reported.

======= "P2332-P2334 Table 3-5 How much sample did you analyze?"

Sample size is added to Tables 3-5.

======= =======

Review 2

======= "1)GCC and EVI are calculated by different wavelength, which reflects the different spectral characteristics of vegetation. You need to link the phenological trajectory of each index (Fig. 3) to the spectral implications and physiological phenomena. What stage of phenophase does the spring maximum or fall minimum in GCC and EVI respectively indicate? Please discuss the large biases between remote sensing and near-surface phenology based on the spectral difference."

Interpreting phenology dates derived from spectral indices in terms of biological events, or phenophases, is one of the goals of this study, as stated in the abstract on P2306 L3-L6. The results presented on P2316 L5-L28, and discussed in the discussion section, use visual assessments and GCC-derived near surface phenology dates to accomplish this goal. To clarify the points raised in this comment, we propose several revisions to

the manuscript.

To clarify the correspondence of phenophase transitions identified by visual assessment and metrics derived from analysis of GCC time series, P2319 L21 is revised as follows:

>Time series estimates of the start of spring at the near-surface scale are generally well-correlated with visual assessment of the first appearance of leaves (Fig. 4a), the stage of leaf phenology which immediately follows budburst. This indicates that the SOS metric represents the release of ecodormancy in buds on deciduous trees, the stage of bud development at which limitations of environmental factors are removed (Basler and Korner, 2014).

We revise P2320 L11-20 as described above to clarify the link between the spring maximum in GCC and leaf physiology.

The link between autumn phenophase transitions identified by visual assessment and GCC derived metrics is discussed on P2316 L17-28.

We do not compare the visually assessed dates from camera images to the EVI dates from remote sensing as the both the methods and data sources are fundamentally different.

We expand and clarify discussion of spectral differences by revising P2320 L23-28 as described above.

======= "2)The comparison between the near-surface and remote sensing results would include both implications of the spatial representativeness and the spectral difference between GCC and EVI. You can calculate GCC also from satellite data. When you compare GCC derived from near-surface and satellite, it will be more clarified."

We add to P2311 L13 as described above to address this comment.

======= "3)Authors estimated phenology in a broad geographic range of deciduous forests, and showed the scatter plots of the near-surface and remote sensing phenology linking with latitude (Fig. 4 and Fig. 5). Some discussions from geographical and ecological aspects of phenology are expected. And please compare these results with previous knowledge of phenology in the same region."

To address this comment, we conducted additional analysis and propose the following additions to the methods and results sections:

Insert at P2314 L20 (methods): >To characterize geographical patterns and environmental drivers of phenology, we conducted multiple linear regressions of phenology dates using two predictors: a location predictor consisting of site latitude and elevation, and a climate predictor consisting of average daily temperature and cumulative precipitation during the periods April-May for spring transitions, and September-November for autumn transitions, using the DAYMET data set (http://daymet.ornl.gov).

And insert at P2316 L28 (results): >3.3 Climate and geographical analysis of phenophase transitions

>Phenology dates correlate approximately with latitude (Fig 4), although for deciduous forests in eastern North America this relationship is confounded by site elevation according to Hopkin's Law (Hopkins, 1919), as well as local weather (Richardson et al., 2006), both of which affect deciduous tree leaf phenology. We compared the effects of site location and local weather on phenology by calculating a multiple linear regression of phenophase transition dates on site latitude and elevation, and a separate regression on average temperature and cumulative precipitation during the periods April-May for spring transitions, and September-November for autumn transitions.

>In spring, we found that SOS was delayed 1.9±0.3 (regression slope ± standard error) days per degree latitude and 0.5±0.1 days per 30 m in elevation, each about half of what Hopkin's Law predicts, and similar to the delay of leaf unfolding of 0.3 to 1.0 days per 30 m elevation in an altitudinal study of beech and oak trees in southern France (Vitasse et al., 2009), as well as 0.8 days per 30 m elevation in a study of a

hardwood forest in New Hampshire (Richardson et al., 2006). In autumn, the effect of latitude was more pronounced as EOF advanced 2.9±0.3 days per degree latitude, but elevation was not significantly different from zero with an advance of 0.1±0.1 days per 30 m in elevation.

>From the weather analysis, we found that SOS for deciduous trees advanced 3.5±0.3 days per degree Celsius mean April-May temperature, within the range observed in experimental warming studies of deciduous tree leaf phenology of 1-7 days per degree Celsius (Morin et al., 2010; Norby et al., 2003). SOS was relatively insensitive to precipitation, with a delay of 0.02±0.01 days later per mm cumulative precipitation over this period. In autumn, MOF was delayed 3.6±0.4 days per degree Celsius average September-November temperature, but again precipitation effects were not significantly different from zero. These findings are consistent with studies indicating that eastern deciduous forest phenology is generally insensitive to observed variation in precipitation (Dragoni and Rahman, 2012), however the effects of precipitation may influence autumn phenology through soil water balance (Archetti et al., 2013). From the climate analysis we conclude that temperature has significant effects on deciduous forest phenology in the spring and fall, while precipitation does not. From geographical analysis we find that latitude affects the timing of spring and fall phenology, but that elevation effects are only significant in spring.

======= "Table 1: 13 Study sites are shown in fig. 1, but 11 sites in this table. Please describe all the sites, and add the information about dominant plant species and the MODIS Land cover category for each site."

Two sites, Queens and Groundhog, were not originally included in the table because they are in Canada and no NLCD data exists for them. We located additional Canadian land cover data at the same spatial resolution as the NLCD data and now include these sites in Table 1. We also add an additional column to Table 1 for the MODIS land cover data from P2308 L22-L26.

Due to additional land cover data, we now include the Canadian sites in the land cover analysis shown in revised Figure 6 (Figure 3 of comment response), with revised caption:

>Scatter plot of bias in the end of spring (EOS) between near surface GCC date estimates and remote sensing NBAR-EVI estimates using the generalized sigmoid method. Fractional forest cover is defined as the fraction of 30 meter resolution pixels in the deciduous land cover class plus half of the fraction of pixels in the mixed forest class at each study site.

And revise P2317 L18 >r2 = 0.73, p < 0.001

Dominant plant species were not available at several study sites, so this information was not included in analysis.

======= “Page 2314 Line 14 -16, Table Fig. 3: How did you define the start and end of fall in smoothing and interpolation model?”

There is a single fall phenology date estimated using the smoothing and interpolation method, using the maximum of fall redness as described on P2314 L14-L16.

======= “Please add the phenology dates (SOF, EOF) in Fig. 3G.”

Figure 3 is updated with these labels.

======= “Fig. 3: What are the physiological meanings for the minimum values and the later peak of GCC in fall? Was the peak date of RCC equal to the minimum date of GCC?”

The date of GCC minimum in autumn shown in Fig. 3, Oct 4, 2009, is similar to the date of RCC maximum, Oct 8; the physiological interpretation of maximum RCC is the date of brightest fall colors during leaf senescence, as shown in Table 3. From examination of the image at Arbutus Lake on the later peak of GCC on Oct 16, 2009, shown below (Fig 4 of comment response), this date appears to correspond to abscission in the

overstory revealing green leaves on trees in the understory.

However these features are not distinctive in the GCC time series of all study sites. In general across all sites, the peak date of RCC is closer to the end of fall (EOF) value derived from greenness than the start and middle of fall (SOF and MOF), as implied by Table 3. The typical progression of GCC in autumn consists of an initial decrease as leaves begin to yellow, followed by more rapid decrease as yellowing intensifies. Then as leaves begin to turn red, GCC reaches a minimum, and RCC reaches a maximum. When leaves begin to fall off, RCC and GCC decrease and increase, respectively, to their dormant season levels, not because of an increase in greenness but because of a decrease in red leaves in the canopy.

======= “P2316 Line 10-16: The date of canopy maturity derived from near-surface was biased about 9 days earlier than the visual assessment, which still had large uncertainty. However, the EOS in EVI was biased about 9 days later than near-surface greenness (Table. 4), which was identical to the EOS by visual assessment. What does the peak greenness mean?”

We revise P2320 L11-20 as described above to address this comment.

======= “Fig. 4: The range of near surface GCC (x-axis) should be the same with that in Fig. 5. The spring and fall phenology dates approximately relate with latitude in Fig. 5, but no relations are found in Fig.4. Why?”

The axes of Figures 4 and 5 are updated to reflect this. Relations between phenology and latitude may be confounded by site elevation and local climate as discussed above. Figure 5 includes additional site years of data, due to data availability and corresponding to sample sizes which are added to Tables 3-5.

References

Archetti, M., Richardson, A. D., O’Keefe, J. and Delpierre, N.: Predicting Climate Change Impacts on the Amount and Duration of Autumn Colors in a

New England Forest, edited by B. Bond-Lamberty, PLoS One, 8(3), e57373, doi:10.1371/journal.pone.0057373, 2013.

Basler, D. and Korner, C.: Photoperiod and temperature responses of bud swelling and bud burst in four temperate forest tree species, Tree Physiol., doi:10.1093/treephys/tpu021, 2014.

Dragoni, D. and Rahman, A. F.: Trends in fall phenology across the deciduous forests of the Eastern USA, Agric. For. Meteorol., 157, 96–105, 2012.

Hopkins, A. D.: The Bioclimatic Law as Applied Entomological Research and Farm Practise, Sci. Mon., 8(6), 496–513, 1919.

Hufkens, K., Friedl, M., Sonnentag, O., Braswell, B. H., Milliman, T. and Richardson, A. D.: Linking near-surface and satellite remote sensing measurements of deciduous broadleaf forest phenology, Remote Sens. Environ., 117, 307–321, doi:10.1016/j.rse.2011.10.006, 2012.

Keenan, T. F., Darby, B., Felts, E., Sonnentag, O., Friedl, M., Hufkens, K., O'Keefe, J., Klosterman, S., Munger, J. W., Toomey, M. and Richardson, A. D.: Tracking forest phenology and seasonal physiology using digital repeat photography: a critical assessment, Ecol. Appl., in press, doi:10.1890/13-0652.1, n.d.

Morin, X., Roy, J., Sonié, L. and Chuine, I.: Changes in leaf phenology of three European oak species in response to experimental climate change., New Phytol., 186(4), 900–10, doi:10.1111/j.1469-8137.2010.03252.x, 2010.

Norby, R. J., Hartz-Rubin, J. S. and Verbrugge, M. J.: Phenological responses in maple to experimental atmospheric warming and CO2 enrichment, Glob. Chang. Biol., 9(12), 1792–1801, doi:10.1111/j.1365-2486.2003.00714.x, 2003.

Richardson, A. D., Bailey, A. S., Denny, E. G., Martin, C. W. and O'Keefe, J.: Phenology of a northern hardwood forest canopy, Glob. Chang. Biol., 12(7), 1174–1188, doi:10.1111/j.1365-2486.2006.01164.x, 2006.

Richardson, A. D., Braswell, B. H., Hollinger, D. Y., Jenkins, J. P. and Ollinger, S. V: Near-surface remote sensing of spatial and temporal variation in canopy phenology, Ecol. Appl., 19(6), 1417–1428, doi:10.1890/08-2022.1, 2009.

Sonnentag, O., Hufkens, K., Teshera-Sterne, C., Young, A. M., Friedl, M., Braswell, B. H., Milliman, T., O'Keefe, J. and Richardson, A. D.: Digital repeat photography for phenological research in forest ecosystems, Agric. For. Meteorol., 152, 159–177, doi:10.1016/j.agrformet.2011.09.009, 2012.

Vitasse, Y., Delzon, S., Dufrêne, E., Pontailler, J.-Y., Louvet, J.-M., Kremer, A. and Michalet, R.: Leaf phenology sensitivity to temperature in European trees: Do within-species populations exhibit similar responses?, Agric. For. Meteorol., 149(5), 735–744, doi:10.1016/j.agrformet.2008.10.019, 2009.

Yang, X., Tang, J. and Mustard, J.: Beyond leaf color: comparing camera-based phenological metrics with leaf biochemical, biophysical and spectral properties throughout the growing season of a temperate deciduous forest, J. Geophys. Res. Biogeosciences, n/a–n/a, doi:10.1002/2013JG002460, 2014.

Interactive comment on Biogeosciences Discuss., 11, 2305, 2014.

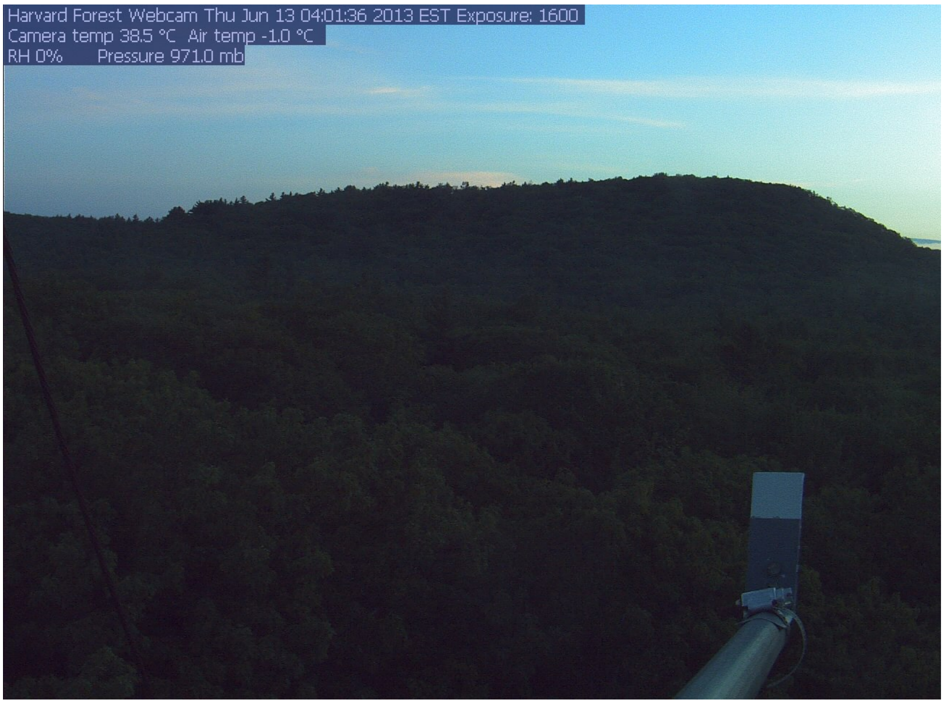

Fig. 1. Sample dark canopy image

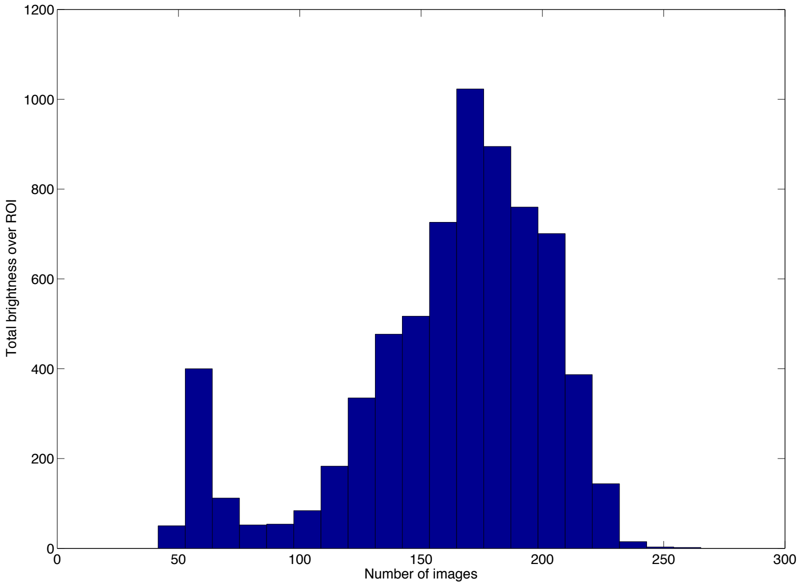

Fig. 2. Histogram of image brightness

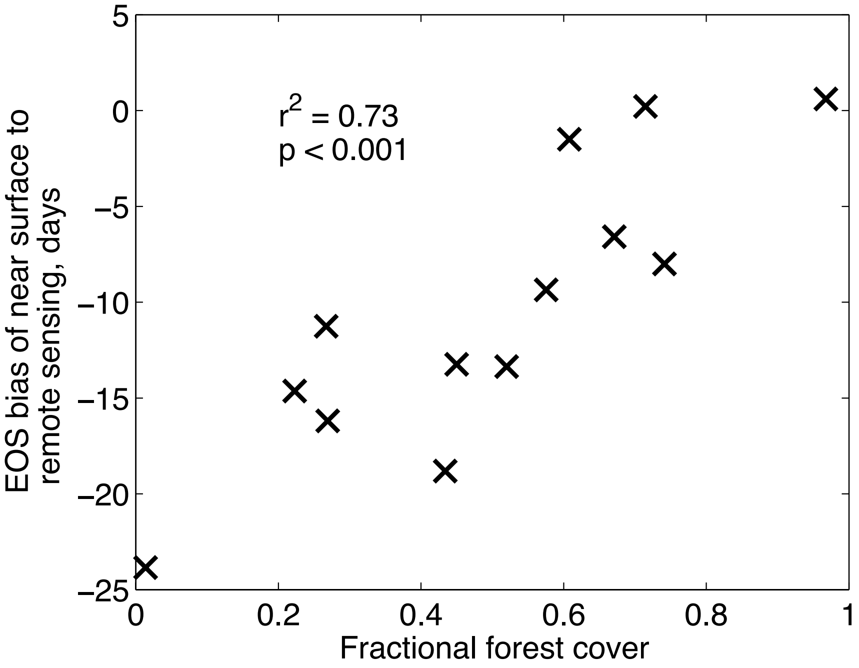

Fig. 3. Revised Figure 6

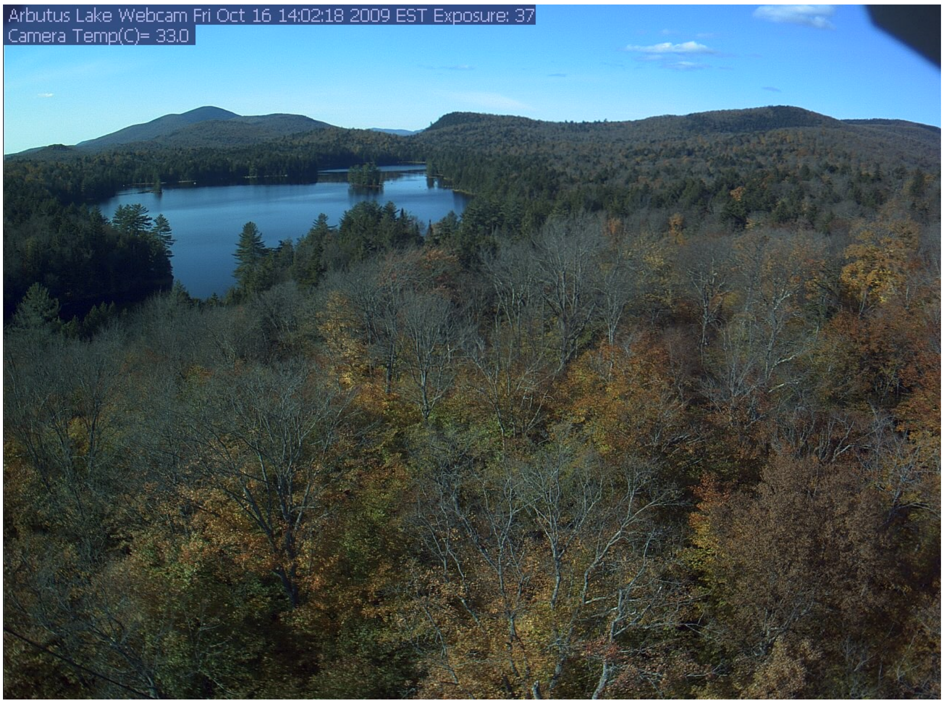

Fig. 4. Understory greenness at later peak of GCC