Band combinations for detecting leaf amount and leaf age in QuickBird satellite and RGB camera images

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Abstract. Leaf amount and leaf age may drive seasonal variation in canopy-scale photosynthetic capacity and carbon balance in the Central Amazon. It is therefore important to measure these phenological attributes. We used linear discriminant analysis and a leave-one-out jackknife validation to rank combinations of QuickBird surface reflectance bands and transformed bands for (1) separating leafy from bare tree crowns and (2) separating recently flushed crowns from all other crowns (with older dark leaves or bare). We compared performances of singles and pairs of ten original and transformed bands: R, G, B, NIR, NDVI, EVI, Excess Green, Blue Coordinate, Green Coordinate and Red Coordinate. Among the ten singles, Green Coordinate (with 95% separation), followed by NDVI (93%), best separated leafy from bare crowns. EVI performed poorly (83%). Among pairs of transforms, any combination of the visible band "coordinates" obtained 100% separability. Excess Green (EG) best discriminated recently flushed leafy crowns from all other crowns. We used EG detection of new leaf flush to obtain ages of leaf cohorts by crown, in a time-series of 23 images at ten day intervals from a tower-mounted RGB camera. For crowns that undergo massive rapid flush, the "date of birth" of each crown´s leaf cohort was detected as a unimodal hump in the temporal trace of its EG value. We conclude that the RGB bands and their transforms, available from conventional cameras, can estimate both leaf age and leaf amount in the upper canopy.

Key-words: Amazon, greenup, leaf phenology, excess green coordinate, vegetation index

1. Introduction

Our objectives here are to (1) rank the performance of different combinations of four bands (R, G, B and NIR) and their transforms for distinguishing upper canopy tree crowns having different leaf amounts and leaf ages and (2) using the band or transform most suitable for detecting young fully expanded leaves, determine the time of leaf flush of individual crowns in a time series of images obtained from a tower-mounted camera. Our underlying interest is to determine if the R, G and B bands available in conventional cameras are adequate for monitoring seasonal changes in leaf amount and the leaf age mix (leaf demography) in the upper canopy of Amazon forest.

2. Methods

We obtained a multispectral QuickBird image of *terra firme* in the Ducke Forest Reserve (-2.975°, -59.950°) near Manaus. Acquired in August of 2004, the image has a nadir view and solar zenith angle of 30^{o}. We converted the B, G, R and NIR digital numbers to surface reflectance using FLAASH (MODTRAN4).

We made a true-color RGB composite to select 40 large tree crowns, divided evenly into four pheno-classes: leafy with bright green leaves, leafy with dark green leaves, deciduous with light grey branches, and deciduous with dark grey branches. These 40 trees were all located on plateaus to avoid topographic shadows. Aided by the 60 cm resolution panchromatic band, we digitized masks for extracting pixel statistics of each of the 40 crowns in the 2.4m resolution QuickBird true-color image. We obtained the mean reflectance of each crown for the four original bands (B, G, R, NIR) and for six transformed bands: Blue Coordinate, Green Coordinate, Red Coordinate, Excess Green, and the vegetation indices EVI and NDVI. The first three of these derived bands were obtained as shown by Equation 1 for the Green Coordinate (Richardson at al. 2013). Excess Green is shown in Equation 2.

$$GC = G /(R+G+B) \quad (1)$$
$$EG = 2*G – (R+B) \quad (2)$$

where R, G and B correspond to red, green and blue surface reflectances, respectively, GC is the Green Coordinate transformed band and EG is the Excess Green transformed band.

We used linear discriminant analysis and a post-hoc leave-one-out jackknife validation to obtain performance estimates for the separation of crown phenology classes in different band spaces. This was done for single and paired combinations of the ten bands. We first looked at separability of the 20 leafy crowns x 20 bare crowns. This was our test for detection of leaf amount. We then compared separability of crowns with a recent flush of young fully expanded leaves, which are light green in color to our eyes, against the other three classes lumped together -- dark leafy crowns, light grey deciduous crowns and dark grey deciduous crowns. This was our test for ability to monitor leaf age, i.e. recognize the time of formation of a new bright green leaf cohort in each crown.

After choosing the single original band or transform most suitable for detecting young fully expanded leaves, we examined that band´s behavior in a time series of images obtained from a tower-mounted RGB camera (Stardot Netcam XL), in the hope of detecting a single peak along the timeline of that indicator for each of several crowns. If detected and distinct, this peak should correspond to the date of formation of a new leaf cohort in the specific crown being followed. The camera was mounted 45 m above the canopy of a plateau forest at the Amazon Tall Tower (ATTO) site (-2.143°,-59.000°). The time series had 23 images at ten day intervals. Images were all obtained under diffuse illumination in the late morning with the sun behind the camera, i.e. an obliquely western view. The 23 images were adjusted to match spatially and radiometrically. The latter was accomplished by histogram matching (Leonardi et al. 2003) to standardize illumination[1]. The tower camera image covered about 300 upper canopy crowns which could be visually distinguished and vectorized.

The QuickBird and tower camera images were always analyzed on a crown-by-crown basis using crown masks to obtain the average value of a band for each crown. A crown-by-crown approach was adopted since individual trees may present different "colors" as a function of leaf age or species. Furthermore, massive flushing is known to occur over the dry months on a crown by crown basis in most of the upper canopy trees and vines in the Central Amazon (Brando et al. 2010, Nelson et al. 2014).

3. Results and Discussion

[1] This also removes detectability of seasonal variation in average greenness or deciduousness across the entire image, but we are looking for a brief hump-shaped signal (rising from deciduous to bright-green stage then dropping to dark-green stage) in the timeline of each individual crown. For the intercalibration, we used only background parts of the image where crowns are small on the images. Massive phenological changes in a few large crowns in the foreground of the image, if included, would reduce the quality of the intercalibration.

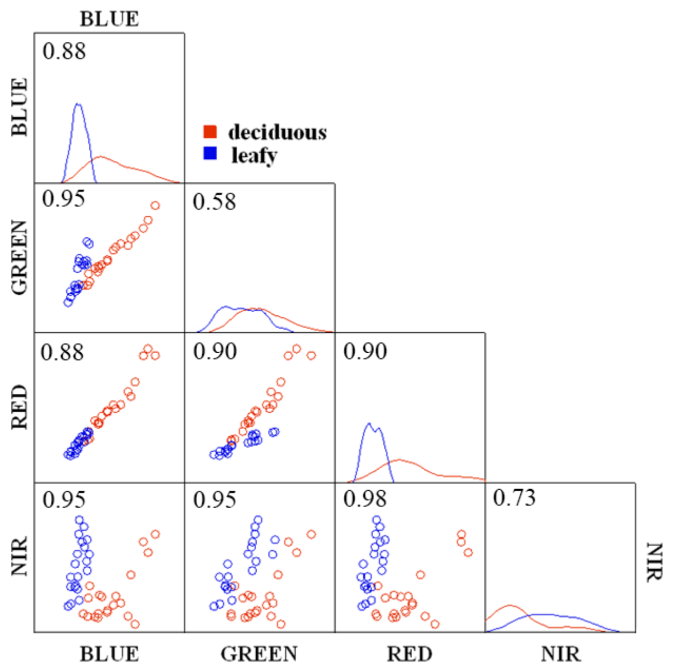

Figure 1. Separation of leafy and deciduous crowns by paired (scatterplots) and single bands (curves, tops of columns) for the four original QuickBird bands. Numbers inserted in panels are jackknife classification scores (scale of 0-1.0).

We first present results for separating all leafy from all deciduous crowns using the original QuickBird bands expressed in surface reflectance. No single untransformed band nor any pair of untransformed bands was capable of separating leafy and deciduous crown classes with 100% accuracy. At 98%, the band space NIR x Red came close to providing complete discrimination of leafy versus woody crowns. Figure 1 shows the performance of all pairs of these four original bands as a matrix of scatterplots. Inside each panel is the jackknife classification accuracy of that particular band space. The maximum possible jackknife value is 1.0. At the top of each column are two kernel curves and a jackknife value, which show the degree of discrimination of leafy and deciduous trees using just one band.

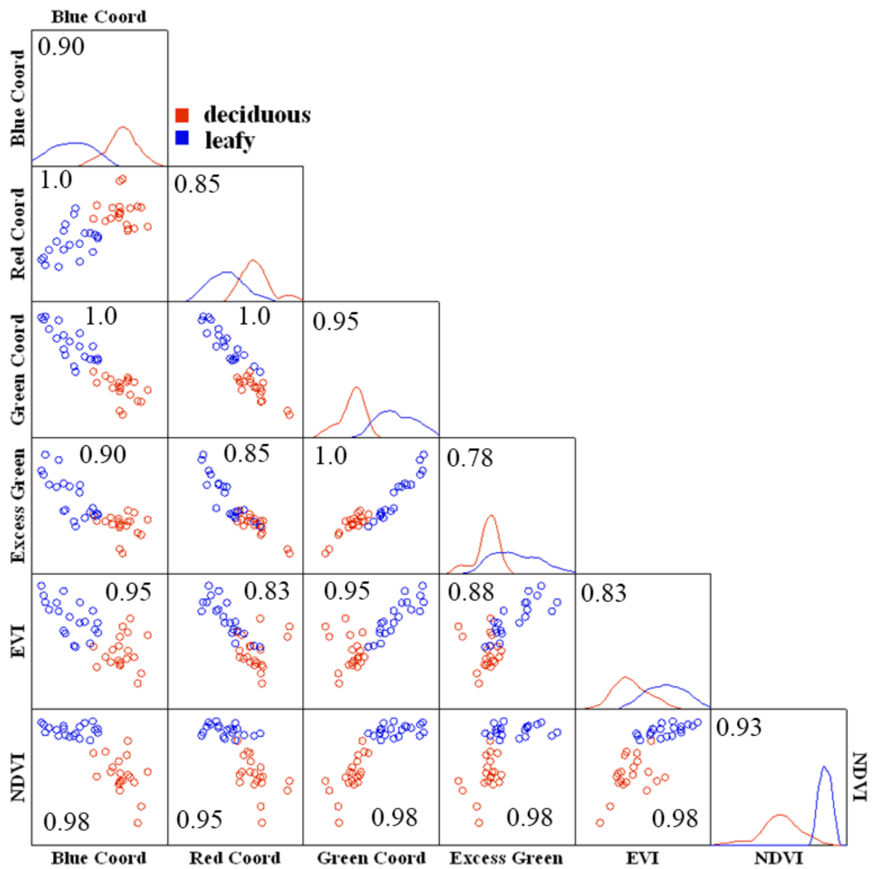

Figure 2. Separation of leafy x deciduous crowns by all pairs (scatterplots) and singles (curves, tops of columns) of the six transformed QuickBird bands. Numbers in the panels are jackknife classification scores.

Figure 2 shows all pairs of the six transformed bands. The Red, Green and Blue Coordinates can be thought of as shade-normalized versions of the original Red, Green and Blue bands. Normalization has improved their capacity to discriminate leafy and deciduous crowns, leading to 100% jackknife accuracy for all possible pairings of RC, GC and BC. Excess Green paired with Green Coordinate also provided 100% accuracy. These highest performing transforms are derived exclusively from Red, Green and Blue bands with no contribution from the NIR band. Interestingly, NDVI by itself was worse than the band-space NIR x Red, though NDVI did come close to 100% accuracy in several pairings with transformed bands. When the six transformed bands were evaluated singly, the best discrimination of leaf amount was provided by the Excess Green Coordinate alone (95%) followed by NDVI alone (93%). EVI performed poorly (83%).

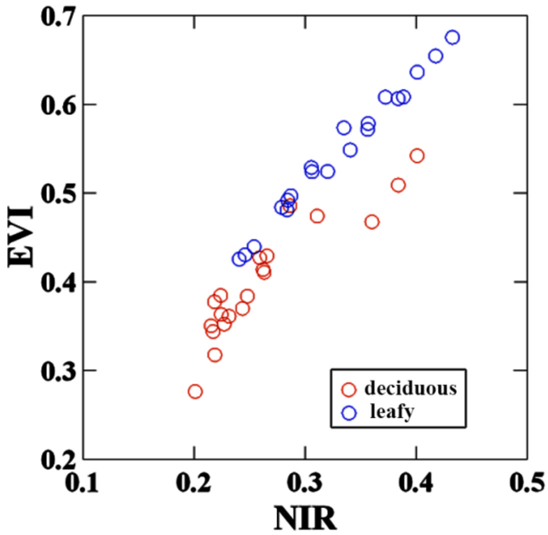

Figure 3. Strong correlation between NIR reflectance and EVI vegetation index.

Why is EVI by itself unable to separate two crown classes with very large differences in leaf amount? A scatterplot of NIR x EVI shows the two are highly correlated, with R^2 = 0.88 (Figure 3). Since the NIR band is not shade-normalized, this supports the idea that EVI is affected by shade content of a pixel, as previously argued by Galvão et al. (2011). NDVI is saturated in all 20 leafy crowns and separates these better (than does EVI) from the 20 deciduous crowns. NDVI is not saturated in the deciduous crowns (Figure 2, bottom row).

One should keep in mind that the *a priori* categorization of crown types used in this test was based on the Red, Green and Blue bands. While these bands do emulate what we see with our eyes when identifying bare branches and leaves, the crown classes might have been slightly different had we used a color composite that included the NIR band for our *a priori* recognition of leafy and deciduous crown classes. These tests should be repeated with very high resolution four-band images that can resolve individual leaves and branches. It is also important to use upper canopy branches (as we did here) because they constitute the woody material seen by orbital sensors. These branches tend to be brighter in all four bands than understory branches.

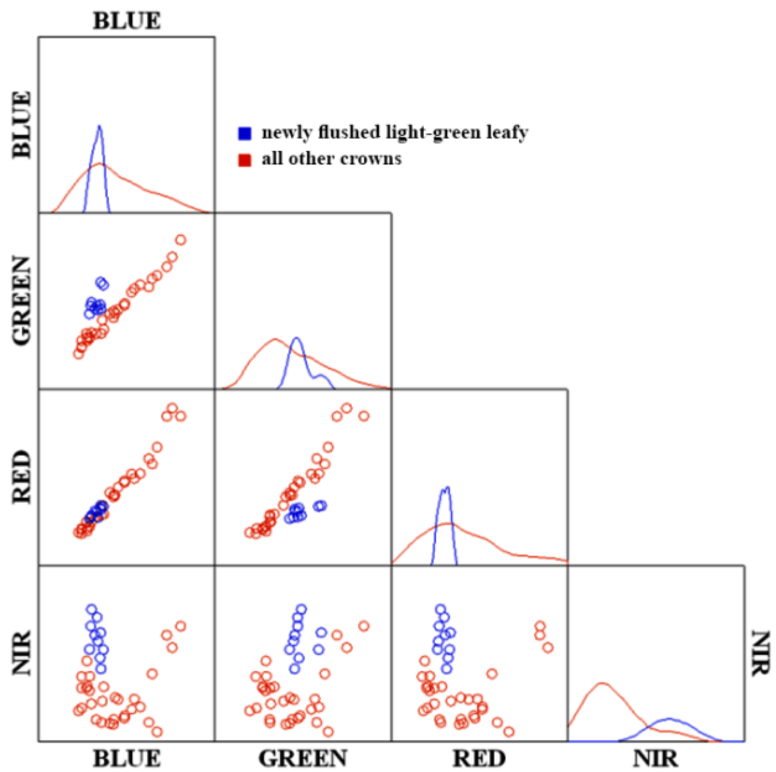

Figure 4. Separation of recently flushed green crowns from all other crowns by pairs (scatterplots) and singles (curves, tops of columns) of the four original QuickBird bands.

We now move on to our second question: What are the best QuickBird bands for discrimination of crowns with recently flushed fully expanded leaves? Results for all single band and two-band spaces are shown in Figure 4 for the four original bands and in Figure 5 for the six transformed bands. In these two figures we do not report jackknife values because visual inspection is sufficient to show that the

Excess Green band by itself (and therefore also in combination with any of the other transformed bands) provides a strong separation.

This result is expected given that young but fully expanded leaves do not yet have their full complement of chlorophyll, making them light green in color. As this pigment increases, maturing leaves become dark green (Lieberei 2007, Yang et al. 2014). This stage of leaf maturation will not be separated from older stages by the NIR band as it is unaffected by changes in pigment content.

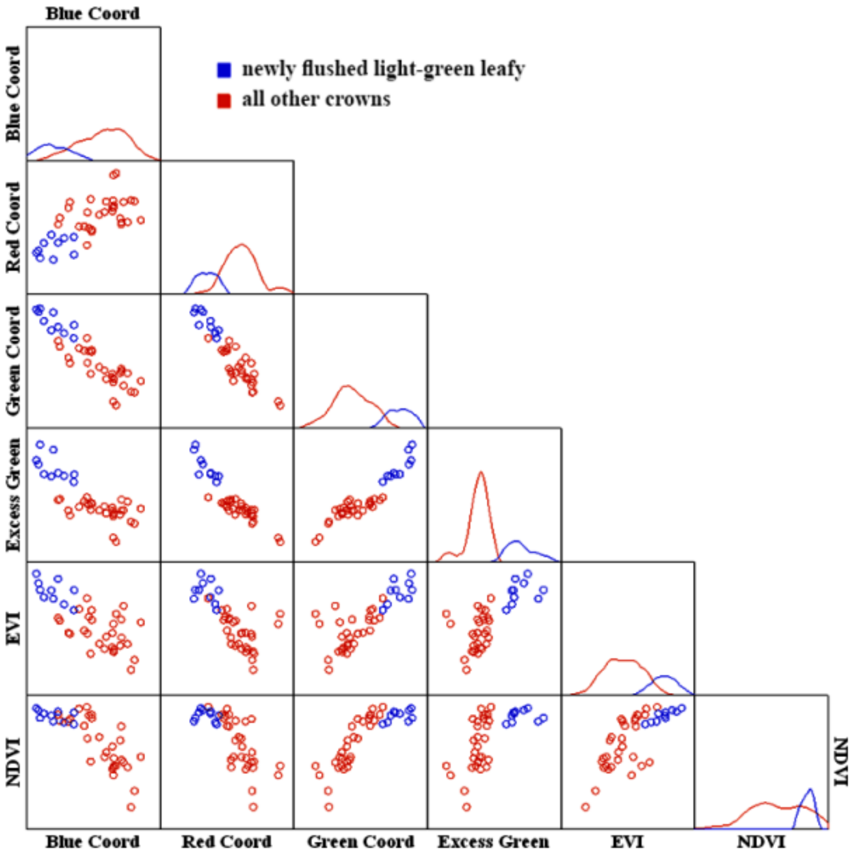

Figure 5. Separation of recently flushed green crowns from all other crowns by pairs (scatterplots) and singles (curves, tops of columns) of all transformed QuickBird bands. Note superior performance of Excess Green.

With this indication that the Excess Green Coordinate should provide the best detection of flushing events in each crown, we plotted the temporal trace of Excess Green for three crowns visible from the ATTO tower over a period of 230 days (Figure 6). Massive leaf flush coincides with a unimodal hump in the Excess Green for each individual crown. This is also observed for the whole forest canopy in temperate forests (Richardson et al. 2007). We visually checked this pattern for 50 individual crowns at the ATTO site. For most of these, the Excess Green temporal trace was able to show exactly when each crown changed its leaves. The same pattern was observed for the Green Coordinate, but the Excess Green showed greater contrast, particularly when there was a leaf drop prior to flushing.

This unimodal hump is often characterized by a valley (lower values) when the crown briefly drops all leaves prior to flushing, then a steep positive slope as the crown flushes new leaves. This is followed by a gradual drop to the steady long-term value of dark green as chlorophyll increases (Yang et al. 2014) and as the leaf surface is covered with epiphylls and dark fungi (Roberts et al. 1998, Toomey et al 2009). Gradual leaf losses from herbivory and physical damage may also contribute to gradual long-term drop in Excess Green values of a crown until the next massive leaf flush. For about 3-8 months after flushing, even as Excess Green drops, the canopy photosynthetic capacity remains high (Restrepo-Coupe et al. 2013, Wu et al. 2013, Albert et al. 2014), accompanying the NIR reflectance which does not decrease so quickly as Green reflectance. By furnishing the time of flushing of each crown, Excess Green allows us to construct a leaf age pyramid for each month of the year and infer the seasonal period of highest photosynthetic capacity of the forest as a whole.

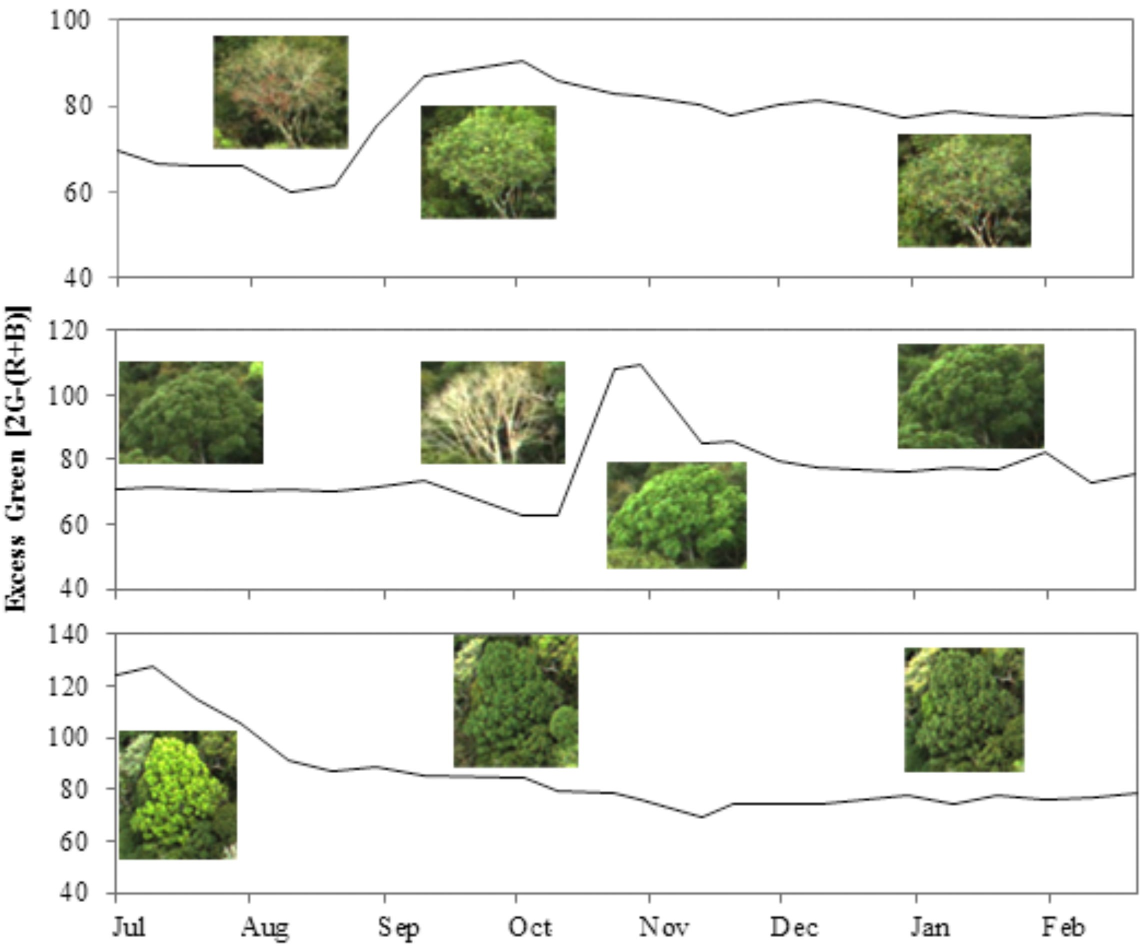

Figure 6. Temporal traces of three tree crowns, showing unimodal hump in Excess Green coordinate, coincident with massive leaf flush events. Over half of all upper canopy crowns have this massive flush behavior.

4. Conclusions

(1) The EVI vegetation index by itself did not consistently distinguish all leafless tree crowns from all crowns with dense leaves. NDVI performed better than EVI in this respect, but both of these one-dimensional derivatives lost some of the discrimination power present in the two-dimensional band space NIR x Red.

(2) The Blue, Green and Red bands, after being normalized by the sum R+G+B, consistently discriminated all leafy and deciduous crowns in any of their two-dimensional band spaces.

(3) The Excess Green band, a one-dimensional derivative of the Blue, Green and Red bands, was capable of detecting the "date of birth" of new leaf cohorts in trees which experience massive leaf flush, thus allowing an estimation of leaf age mix (leaf demography) over time.

(4) The bands in inexpensive conventional RGB cameras mounted on towers, allow measurement and monitoring of both leaf age and leaf amount.

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References

Albert, L.; Wu, J.; Prohaska, N.; Camargo, P.B.; Cosme, R.; Huxman, T.E.; Saleska, S.R. Leaf demography and physiology of the Tapajós National Forest: could phenology cause a forest-level increase in gross primary productivity during the dry season? In: **AGU** (American Geophysical Union, Fall Meeting), 2014, San Francisco (CA). Paper #B11G-0108. Available in: < https://agu.confex.com/agu/fm14/meetingapp.cgi#Paper/26480>. Accessed: Nov 9 2014.

Brando, P.M.; Goetz, S.J.; Baccini, A.; Nepstad, D.C.; Beck, P.S.; Christman, M.C. Seasonal and interannual variability of climate and vegetation indices across the Amazon. **PNAS**, v. 107, n. 33, p. 14685-14690, 2010.

Galvão, L.S.; Santos, J.R. Dos; Roberts, D.A.; Breunig, F.M.; Toomey, M.; de Moura, Y.M. On intra-annual EVI variability in the dry season of tropical forest: a case study with MODIS and hyperspectral data. **Remote Sensing of Environment**, v. 115, n. 9, p. 2350-2359, 2011.

Leonardi, S.S.; Souza, S.M.; Fonseca, L.M.G. Comparação do desempenho de algoritmos de normalização radiométrica de imagens de satélite. In: Simpósio Brasileiro de Sensoriamento Remoto (SBSR), 11., 2003, Belo Horizonte. **Anais...** São José dos Campos: INPE, 2005. Artigos, p. 2063-2069. CD-ROM, On-line. ISBN 85-17-00017-X. Available in: <http://marte.sid.inpe.br/col/ltid.inpe.br/sbsr/2002/11.14.16.57/doc/15_204.pdf>. Accessed: 08 nov. 2014.

Lieberei, R. South American leaf blight of the rubber tree (*Hevea* spp.): new steps in plant domestication using physiological features and molecular markers. **Annals of Botany**, v. 100, n. 6, p. 1125-1142, 2007.

Nelson, B.W.; Tavares, J.V.; Wu, J.; Valeriano, D.M.; Lopes, A. P.; Marostica, S.F.; Martins, G.; Prohaska, N.; Albert, L.; Araujo, A.C.; Manzi, A.O.; Saleska, S.R.; Huete, A. R. Seasonality of Central Amazon forest leaf flush using tower-mounted RGB camera. In: **AGU** (American Geophysical Union, Fall Meeting), 2014. Paper #B11G-0107. Available in: < https://agu.confex.com/agu/fm14/meetingapp.cgi#Paper/7861>. Accessed: Nov 8 2014.

Restrepo-Coupe, N.; Rocha, H.R.; Hutyra, L.R.; Araujo, A. C.; Borma, L. S.; Christoffersen, B.; Cabral, O.M.R.; Camargo, P.B.; Cardoso, F.L.; Costa, A.C.L.; Fitzjarrald, D.R.; Goulden, M.L.; Kruijt, B.; Maia, J.M.F.; Malhi, Y.S.; Manzi, A.O.; Miller, S.D., Nobre, A.D.; von-Randow, C.; Sá, L.D.A.; Sakai, R.K.; Tota, J.; Wofsy, S.C.; Zanchi, F.B.; Saleska, S.R. What drives the seasonality of photosynthesis across the Amazon basin? A cross-site analysis of eddy flux tower measurements from the Brasil flux network. **Agricultural and Forest Meteorology**, v. 182-183, p. 128-144, 2013.

Richardson, A.D.; Jenkins, J.P.; Braswell, B.H.; Hollinger, D.Y.; Ollinger, S.V.; Smith, M.L. Use of digital webcam images to track spring green-up in a deciduous broadleaf forest. **Oecologia**, v. 152, p. 323-334. 2007.

Richardson, A.D.; Klosterman, S.; Toomey, M. Near-Surface Sensor-Derived Phenology. In: Schwartz, M. D. (Ed.). **Phenology: An Integrative Environmental Science**. Springer, 2013. cap 22, p. 413- 430.

Roberts, D.A.; Nelson, B.W.; Adams, J.B.; Palmer, F. Spectral changes with leaf aging in Amazon caatinga. **Trees** v. 12, n. 6, p. 315-325, 1998.

Toomey, M., Roberts, D.A. Nelson, B.W. The influence of epiphylls on remote sensing of humid forests. **Remote Sensing of Environment** v.113, n. 8, p. 1787-1798, 2009.

Wu, J.; Restrepo-Coupe, N.; Hayek, M.; Stark, S. C.; Smith, M.; Wiedemann, K.; Marostica, S.; Ferreira, M.; Woodcock, T.; Prohaska, N.; da Silva, R.; Nelson, B. W.; Huete, A. R.; Saleska, S. R. Tropical forest phenology and metabolism: Integrated analysis of tower-mounted camera images and tower derived GPP for interpreting ecosystem scale processes. In: **AGU** (American Geophysical Union, Fall Meeting),2013, abstract #B34A-07. Available in: <http://adsabs.harvard.edu/abs/2013AGUFM.B34A..07W> , 2013. Accessed Nov 9 2014.

Yang, X.; Tang, J.; Mustard, J.F. Beyond leaf color: Comparing camera‐based phenological metrics with leaf biochemical, biophysical, and spectral properties throughout the growing season of a temperate deciduous forest. **Journal of Geophysical Research: Biogeosciences**, v. 119, n. 3, p. 181-191, 2014.