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Using phenological cameras to track the green up in a cerrado savanna and its on-the-ground validation

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ABSTRACT

Plant phenology has gained new importance in the context of global change research, stimulating the development of novel technologies for phenological observations. Regular digital cameras have been effectively used as three-channel imaging sensors, providing measures of leaf color change or phenological shifts in plants. We monitored a species rich Brazilian cerrado savanna to assess the reliability of digital images to detect leaf-changing patterns. Analysis was conducted by extracting color information from selected parts of the image named regions of interest (ROIs). We aimed to answer the following questions: (i) Do digital cameras capture leaf changes in cerrado savanna vegetation? (ii) Can we detect differences in phenological changes among species crowns and the cerrado community? (iii) Is the greening pattern detected for each species by digital camera validated by our on-the-ground leafing phenology (direct observation of tree leaf changes)? We analyzed daily sequences of five images per hour, taken from 6:00 to 18:00 h, recorded during the cerrado main leaf flushing season. We defined 24 ROIs in the original digital image, including total or partial regions and crowns of six plant species. Our results indicated that: (i) for the studied period, single plant species ROIs were more sensitive to changes in relative green values than the community ROIs, (ii) three leaf strategies could be depicted from the species' ROI patterns of green color change, and (iii) the greening patterns and leaf functional groups were validated by our on-the-ground phenology. We concluded that digital cameras are reliable tools to monitor high diverse tropical seasonal vegetation and it is sensitive to inter-species differences of leafing patterns.

1. Introduction

Leaf flushing and senescence are important events in plant life cycles and fundamental to understand a range of processes in the ecosystem due to their impact on growth, water status, gas exchange and nutrient cycling (Morisette et al., 2009; Negi, 2006; Reich, 1995). The plants' growing season plays a crucial role in the carbon balance and in the productivity of terrestrial ecosystems (Keeling et al., 1996; Loustau et al., 2005; Rotzer et al., 2004), controlling spatial and temporal patterns of carbon and water exchange between the forest and atmosphere (Schwartz et al., 2002; White et al., 1999). The time, length, and intensity of the leaf growing season are closely linked to the proportion of leaf exchange functional types (e.g. evergreen, deciduous and semi-deciduous species). Those plant functional types define the seasonal patterns of leaf changes and the dynamics of the ecosystem processes (Gholz et al., 1976; Negi, 2006; Reich et al., 1997; Shaver, 1981).

The relevance of plant phenology as a reliable indicator of species' responses to global climate change has stimulated the development of new technologies for phenological monitoring (Parmesan and Yohe, 2003; Richardson et al., 2009; Rosenzweig et al., 2008; Walther, 2004; Walther et al., 2002). To better understand seasonal patterns and responses of leafing to inter-annual and long-term variation in climate, a variety of approaches to describe temporal changes in the plant canopy have been employed. The traditional on-the-ground phenology, the direct observations of individual plants, preclude large spatial areas, and the interference of the observer is high due to the inherent difficulties to detect the variations on leaf color patterns from leaf budding to senescence in the tropics (Morellato et al., 2010a; Morisette et al., 2009; Richardson et al., 2007). Satellite remote sensing provides spatially extensive information of vegetation changes; however, it is difficult to detect phenological events at species and community levels (Ide and Oguma, 2010). In addition, the temporal resolution and the quality of satellite observations are limited due to clouds and atmospheric

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disturbances (Ahl et al., 2006; Zhang et al., 2006) and still need ground validation (Chambers et al., 2007).

The technique of repeated photographs using digital cameras has been increasingly used for several ecological applications (Crimmins and Crimmins, 2008; Graham et al., 2010). Low cost investment, reduction in size to set up installation, and high resolution data make digital cameras a reliable tool for a range of applications (Morisette et al., 2009), including changes in ecosystem dynamics and structure (Peñuelas and Boada, 2003), growth vegetation and biomass (Crimmins and Crimmins, 2008; Graham et al., 2009), plant stress and nitrogen status (Wang et al., 2004), and crop monitoring (Slaughter et al., 2008).

Recently, “near-surface” remote monitoring with digital cameras has been successfully used as a multi-channel imaging sensor to characterize leaf change patterns in temperate ecosystems, such as: northern hardwood and conifer forests (Graham et al., 2009; Richardson et al., 2007, 2009), mixed beech forest and temperate deciduous forests (Ahrends et al., 2009; Henneken et al., 2013; Ide and Oguma, 2010), deciduous broad-leaved forest (Nagai et al., 2011), subalpine grasslands (Migliavacca et al., 2011) and temperate dry land ecosystems (Kurc and Benton, 2010). After quantifying the RGB (red, green, and blue) color channels, it is possible to estimate, for instance, leaf flushing and senescence, using the green and red channels, respectively (Ahrends et al., 2009; Henneken et al., 2013; Morisette et al., 2009; Richardson et al., 2009). Another important feature is the precise estimation of the starting date of leaf flush season, due to the daily frequency of data acquisition (Morisette et al., 2009; Richardson et al., 2009).

However, image information from digital cameras is still sparse for high-diverse tropical vegetation. In those ecosystems, one image may encompass dozens to more than a hundred of species, whereas temperate vegetation includes a much lower number of species. In this context, we monitored a cerrado savanna during the leafing season to assess the reliability of digital images to detect leaf change patterns in this species rich vegetation. We used our on-the-ground direct plant phenological observations at the same study site to validate the digital data. We aim to answer the following questions: (i) Do digital cameras capture leaf changes in a cerrado savanna vegetation? (ii) Can we detect differences on phenological changes among species crowns and the cerrado community? (iii) Is the greening pattern detected for each species crown by digital cameras validated by our on-the-ground leafing phenology (direct observation of tree leaf changes)? We discuss the implications of our findings for monitoring the dynamics of seasonal tropical vegetations.

2. Materials and methods

2.1. Study area and camera setup

The near-remote phenological system was set up in an 18 m tower (phenology tower) in a Cerrado sensu stricto, a savanna vegetation located at Itirapina (22°10′49.18″S; 47°52′16.54″W, 610 m a.s.l.), São Paulo State, Brazil (Figure S1, Supplementary material). The cerrado sensu stricto (Coutinho, 1978) vegetation does not form a continuous canopy, but presents a dominant woody component six to seven meters high, with some trees reaching up to 12 m high and a continuous herbaceous layer.

The regional climate is Cwa type (i.e., humid subtropical climate) according to Köppen (1931) classification. The average local climate (1972 to 2002) shows a mean annual total rainfall of 1524 mm and mean annual temperature of 20.7 °C, with one warm, wet season from October to March (average of 22 °C and 78% of annual precipitation) and one cold, dry season (average of 18 °C and 16% of annual precipitation) from April to September (Figure S2). During the year of study (2011) the climate seasonality was similar to the average pattern, with a mean temperature of 21.2 °C, but a higher annual total rainfall of 1891 mm due to a very humid January with precipitation over 500 mm (Fig. 1). Climatic data were obtained from the adjacent Climatological Station of the Center for Water Resources and Applied Ecology (CRHEA) of the University of São Paulo, located 4 km from the study site.

A digital hemispherical lens camera Mobotix Q 24 (Mobotix AG — Germany) was placed at the top of the tower attached to an extension arm facing northeast at a mean vertical distance of 10 m from the tree canopy (Figure S1). The camera was well fixed to prevent any movement that could cause shifts in the camera position and thus image

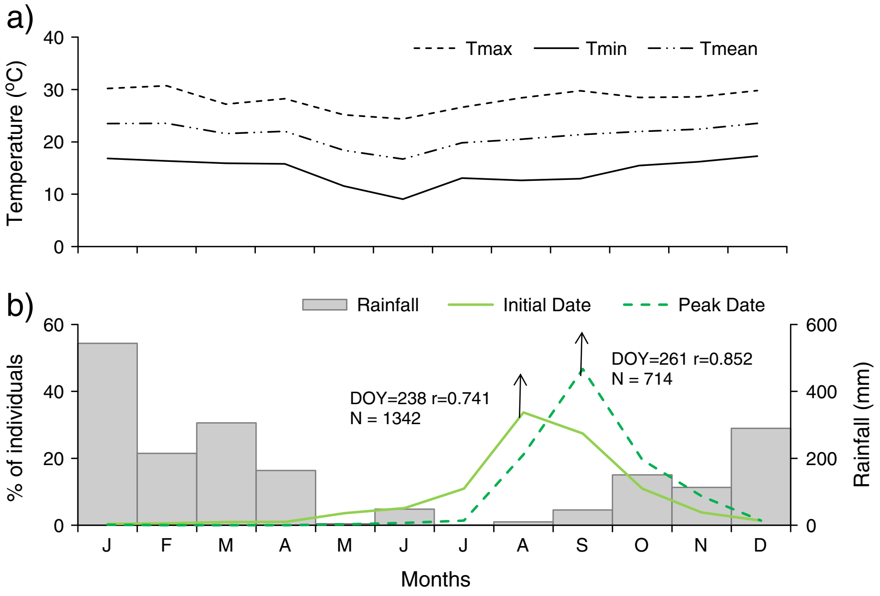


Fig. 1. Temperature, precipitation, and the leaf flushing pattern derived from on-the-ground direct observations of phenology during 2011 at the cerrado study site, Southeastern Brazil. (a) Maximum, mean, and minimum temperature, (b) Bars represent rainfall and lines represent the proportion of individuals at initial date (continuous line) and on the peak date (dotted line) of leaf flushing at the cerrado community. Arrows show the mean start date and peak date of leaf flushing along the year, indicated as the DOY (day of year) and N indicates number of individuals in the analyses. Rayleigh test was significant ($p = <0.01$), and the value of r has no units and indicates the amount of concentration in the data around the mean angle, from zero (when there is so much dispersion that a mean angle cannot be described) to one (when all the data are concentrated at the same direction or angle).

mismatches from one day to another. A timer controlled the camera activity. Camera was set in automatic exposure and white balance, as suggested by Zhao et al. (2012). The energy source was a 12 V Battery charged by a solar panel. We set up the camera to automatically take a daily sequence of five JPEG images (at 1280 × 960 pixels of resolution) in the first 10 min of each hour, from 6:00 to 18:00 h (UC −3; Universal Time Coordinated). The present study is based on the analysis of over 2470 images, recorded at the end of the dry season, between August 29th and October 5th 2011, day of year (DOY) 241 to 278, during the main leaf flushing season (Camargo et al., 2013, Morellato et al., unpublished data, Fig. 1). Sunrise, sunset, and solar elevation angle were 6:03 h, 17:38 h, 58° (DOY 241), and 5:26 h, 17:48 h, 72º (DOY 278), respectively.

2.2. Image analysis

The image analysis was conducted by defining different regions of interest (ROI) in the image, as described by Richardson et al. (2007, 2009), Ahrends et al. (2009) and Henneken et al. (2013). We identified at species level all crowns monitored in the hemispherical image, excluding just the trees on the very edge (Fig. 2d) where the distortion made the tree identification unreliable. The plant identifications were done in the field by directly matching the tree crown in the image with the tree on the ground.

We defined 24 ROIs (Fig. 2b–j), described as follow: (b) whole cerrado: we took the complete image area, excluding just the tower; (c) central area of the whole cerrado image, excluding the edge (radius 30 m); (d) edge area: periphery of the whole cerrado image; (e) to (j) ROIs based on the random selection of six plant species crowns in the hemispheric image, taking into account the smallest overlap with neighboring crowns: (e) *Aspidosperma tomentosum* (N = 3 ROIs); (f) *Caryocar brasiliensis* (N = 4 ROIs); (g) *Myrcia guianesis* (N = 2 ROIs); (h) *Miconia rubiginosa* (N = 6 ROIs); (i) *Pouteria torta* (N = 4 ROIs) and (j) *Pouteria ramiflora* (N = 2 ROIs). The number of ROIs for each species was limited by the occurrence of the individuals in the hemispheric image. Hereafter, the species will be named by their genus, except for *P. torta* and *P. ramiflora*.

For each ROI, a binary image with the same dimensions as the original image was created as a mask. White pixels of a mask indicate the ROI, while the remaining area was filled by black pixels (Fig. 2b–j). We analyzed each ROI in terms of the contribution of the relative brightness of the green color channel (RGB chromatic coordinates in Woebbecke et al., 1995) in relation to the primary colors (red, green, and blue). The normalized RGB chromatic coordinate index used in our analysis is referred as the most suitable index to detect leaf color changes and the most efficient to suppress light variation (Gillespie et al., 1987; Sonnentag et al., 2012; Woebbecke et al., 1995). A custom script was used to analyze each color channel and to compute the average value of the pixels' intensity. We calculated normalized colors of the green color channel, as:

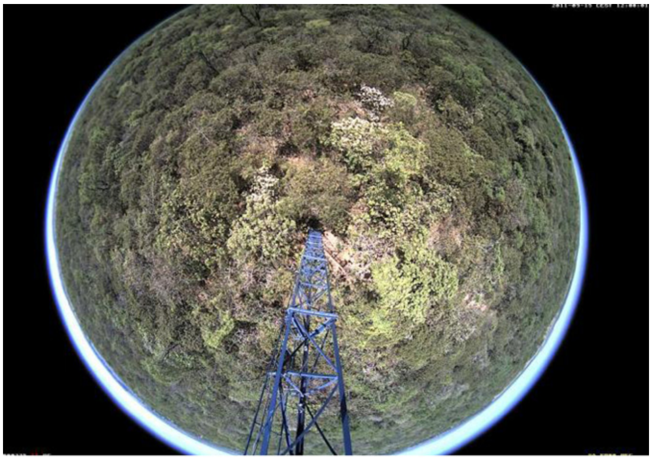
$$\mathrm{Total}_{avg} = \mathrm{Red}_{avg} + \mathrm{Green}_{avg} + \mathrm{Blue}_{avg}$$

$$\mathrm{Green}\ \% = \frac{\mathrm{Green}_{\mathrm{avg}}}{\mathrm{Total}_{\mathrm{avg}}}.$$

Although the index Green% is actually calculated as a proportion, we call it "percent" for convenience.

2.3. Image quality control

To assess the day-to-day stability of the image data acquisition along the growing season, we defined an additional ROI from the tower structure as a reference (Fig. S3) and extracted their averaged RGB color channels. Then, we calculated the coefficient of variation for the red, green and blue color channels time series.



(a) Sample image of the cerrado savanna

(b) whole cerrado (c) central area (d) edge area

(e) *Aspidosperma* (*N*=3) (f) *Caryocar* (*N*=4) (g) *Myrcia* (*N*=2)

(h) *Miconia* (*N*=6) (i) *P. torta* (*N*=4) (j) *P. ramiflora* (*N*=2)

Fig. 2. Sample image of the cerrado savanna (a) recorded by the digital camera on October 15th 2011. Below (b–j) are the masks indicating the regions of interest (ROI) visualized as white areas: (b) whole cerrado savanna, excluding the tower; (c) central area of (b), excluding the edge; (d) edge as seen on (b); (e) *Aspidosperma*; (f) *Caryocar*; (g) *Myrcia*; (h) *Miconia*; (i) *P. torta*; and (j) *P. ramiflora*. A number of ROIs are in parentheses.

Variation along the hours of the day was verified for each ROI. Mean time series for all period along the hours of the day (from 6 h to 18 h) were plotted for the community and individuals species. In general, ROIs presented the highest green values and more stability within midday hours (from 10 h to 14 h, Fig. 3) as previously detected by other authors (Ahrends et al., 2008, 2009; Ide and Oguma, 2010; Richardson et al., 2009; Zhao et al., 2012). Since we analyzed a short time frame during the dry season, and weather conditions were relatively constant in that period, we did not detect diurnal variations related to overcast and sunny days as described by Sonnentag et al. (2012).

To minimize the solar angle effect, avoiding problems in the green values related to seasonal changes and time of the day, we applied the *per*90 method proposed by Sonnentag et al. (2012). We considered all daytime green % values within a moving window of three days, for calculating the 90th percentile of the green % values (Sonnentag et al., 2012).

To check the precision in location of ROIs over time and consequently, if the masks were dislocated in the image or covered by other crowns

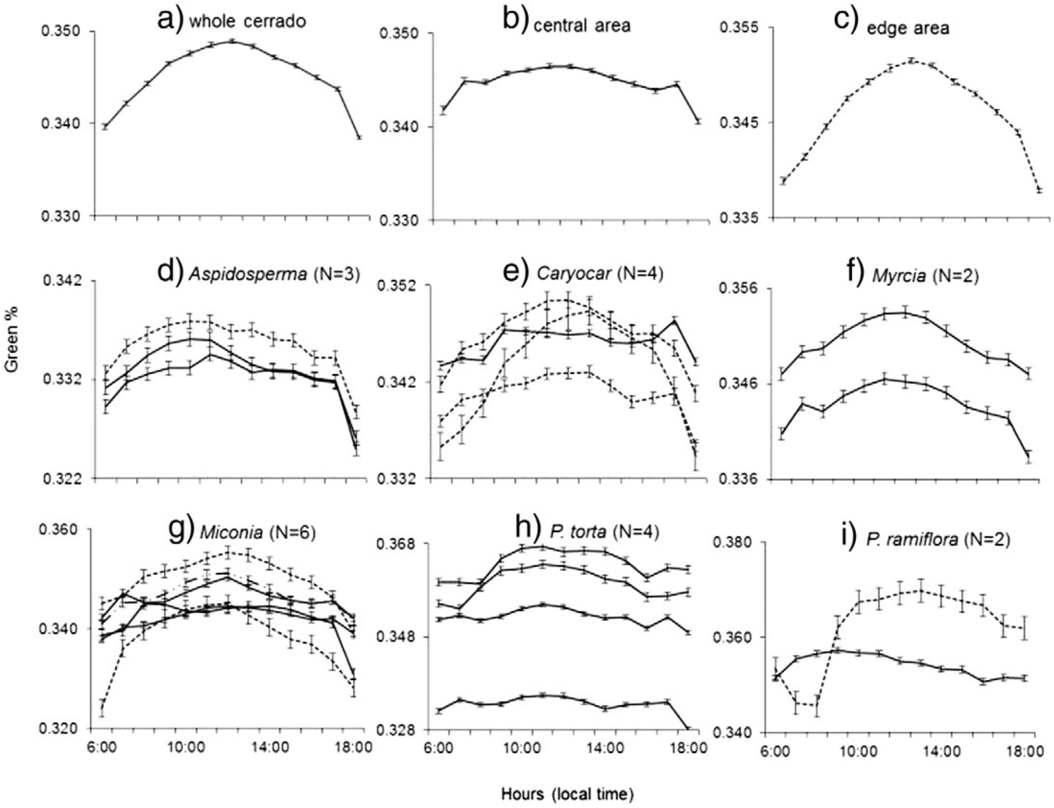


Fig. 3. Mean diurnal patterns of Green% from day of year (DOY) 241 to 278 for all the 24 regions of interest (ROIs). Error bars show 95% of confidence intervals. Black thick lines represent ROIs positioned in the central area of the image, and dashed lines represent the ROIs positioned near the edge of the digital image. *N* indicates number of ROIs.

we made a video with the sequence of images for the studied period. There was no evidence of image mismatch over the time span analyzed (video is available in the Electronic Supplementary Material (ESM) and through our web page http://www.recod.ic.unicamp.br/ephenology/index.php?id=3).

2.4. On the ground validation of digital image phenology

To evaluate the performance of the method and verify the efficiency for monitoring phenological events in the cerrado savanna, we validated our data with monthly on-the-ground direct observations of leaf flushing on 2016 marked individuals in the cerrado savanna study site (see Camargo et al., 2011, 2013, for details on methods).

To verify if the camera-based greening pattern for each ROIs species matches the on-the-ground leaf flushing phenology, we analyzed the frequency of individuals of each species producing new leaves in 2011. To verify if our near-surface phenology fell into the main leafing season, we plotted the on-the-ground leaf flushing phenology for all the community and applied circular statistics analyses to define the mean date and mean start and peak of leaf flushing as proposed by Morellato et al. (2000, 2010b). We use the Rayleigh test to check the significance of mean angle or mean date and, when the mean angle was significant, we use r as a measure of degree of seasonality (Morellato et al., 2000, 2010b). The mean angle or date represents the time around with most individuals was flushing new leaves; the value of r represents the concentration of trees leafing around the mean date. The value of r has no units and indicates the concentration in the data, from zero (when there is so much dispersion that a mean angle cannot be described, — e.g., Fig. 6 c and d) to one (when all the data are concentrated at the same direction or angle, — e.g., Fig. 6a and b). We define the leaf change strategy for each studied species based on the long-term on-the-ground savanna phenology data series at our study site (Morellato et al., unpublished data).

3. Results

3.1. Growing season patterns

The reference RGB values from the tower's ROI did not show a strong variation, except for the early (6–8) and late (16–18) hours of the day (Fig. S3a). Likewise, the low coefficients of variation of the RGB % values from the tower's ROI during the growing season (1.45%, 1.07% and 1.60% for R, G and B, respectively) indicate only small changes along the period of study (Fig. S3b), which did not affect the observed leaf color changes.

In general, the ROIs selected for the cerrado vegetation showed a variation in the green channel along the daily hours (see Fig. 3) as well as in their green pattern along the main leafing season (Fig. 4). The green area in Fig. 4 represents changes in the green %, and the increase in Green% indicates the flush of new leaves which differed not only among the different species (see Fig. 5), but explicitly also among individuals of the same species which are plotted in Fig. 4.

Results based on the 90th percentiles allowed us to identify changes in the Green% pattern for each species' ROI along the growing season. The species' crowns showed different patterns for leaf color change (Fig. 5). *Aspidosperma* and *Caryocar* presented an increase in the green channel along the observed period (Fig. 5a–b), while the opposite pattern was observed for *Myrcia*, *Miconia*, *P. torta* and *P. ramiflora*, with a decrease of greening over time (Fig. 5c–f). However, we observed a within-species variation in the 90th percentile of Green%, with individual ROIs of the same species showing divergent patterns over the leafing season (Fig. S4). For instance, ROIs of individual crowns of *P. torta* and *P. ramiflora* showed either increase or decrease patterns of Green% (Fig. S4 o–t). On the other hand ROIs of *Myrcia* and *Miconia* demonstrated the same pattern of Green% decrease during the main leafing season (Fig. S4 h–n).

However, the 90th percentile (*per90*) of Green% values (Sonnentag et al., 2012) differed between the community and the species ROIs

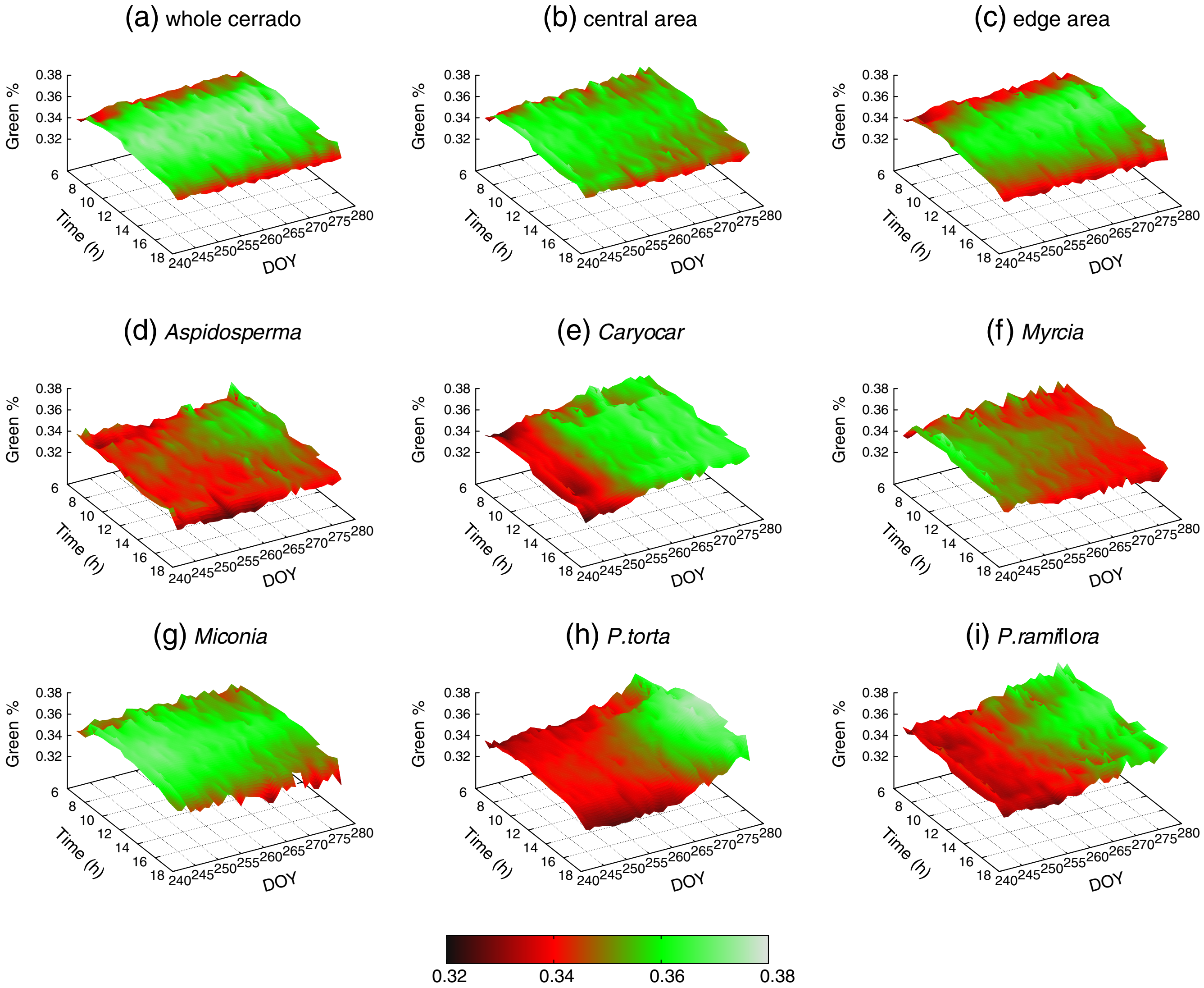


Fig. 4. Changes of the Green% values from digital images taken every hour (6:00 h to 18 h) during the growing season, from day of the year (DOY) 241 to 278 (August 28th to October 3rd, 2011), for individual trees' regions of interest (ROIs) at the cerrado savanna vegetation, Southeastern Brazil.

along the study period. For the community ROIs, we did not detect evident color changes in the short period analyzed, even considering that all images were taken during the peak of the leafing season (Fig. S5).

3.2. Leafing, leaf strategies and on-the-ground validation

The on-the-ground observations of cerrado community leaf phenology in 2011 demonstrated that the leafing season was significantly seasonal, with most individuals starting to flush new leaves in August (mean date of 26-Aug-2011 or DOY 238) and a peak of leaf flush in middle September (mean date of 18-Sep-2011 or DOY 261; Fig. 1). Therefore, our study period (DOY 241 to 278) fell within the main leafing season, even considering the community Green% did not changed over the dry season.

For the six plant species analyzed in the digital images the on-the-ground observations showed different leafing patterns (Fig. 6). Based on the leaf color changes (Fig. 4) and the 90th percentile analyses (Fig. 5), combined with the on-the-ground phenology, we classified the species into three leaf change functional groups: (i) deciduous — species that lose all leaves in the dry season, and flush new ones seasonally and synchronously at the end of the dry season (*Aspidosperma* and *Caryocar*, Fig. 6 a–b); (ii) evergreen — species flushing new leaves continuously along all the year (*Myrcia* and *Miconia*, Fig. 6 c–d); and (iii) semi-deciduous — species that lose part of their leaves in the dry season, and may flush new leaves through the year or more concentrated at the end of dry season or beginning of the wet season (*P. torta* and *P. ramiflora*, Fig. 6 e–f).

Deciduous species presented a marked leaf change, with a seasonal peak of leaf flushing in August (Fig. 6a–b). An opposite pattern was observed for evergreen species for which new leaves were flushing all year and the concentration around the mean date was lower, but also peaking in July and August (Fig. 6c–d). The individuals of semi-deciduous species flushed new leaves all year round (Fig. 6e–f).

4. Discussion

4.1. Digital cameras and the near-remote phenology of cerrado savanna

Digital camera was a reliable tool to monitor leaf phenological changes in the highly-diverse cerrado vegetation. ROIs time series present the highest values for the green curves during the midday hours (noon) (Ahrends et al., 2008, 2009; Sonnentag et al., 2012), except for *Aspidosperma* with the highest green values around 9:00 and 10:00 h. The hours from 8:00 to 11:00 were suggested as the best

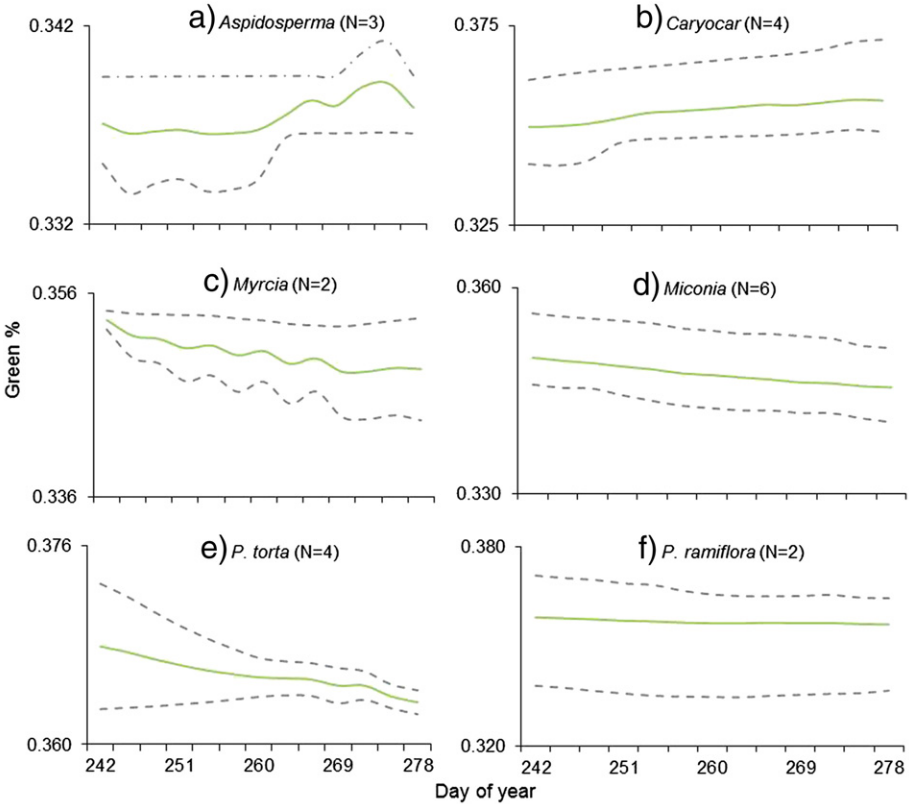


Fig. 5. Mean three-day 90th percentiles of Green% during the leafing season for each species' ROIs in the cerrado savanna, Southeastern Brazil. (a) *Aspidosperma*; (b) *Caryocar*; (c) *Miconia*; (d) *Myrcia*; (e) *P. torta*; (f) *P. ramiflora*. Green lines represent the mean 90th percentiles of Green% for the species; dashed lines represent the maximum and minimum values, respectively (for the masks of each ROI see Fig. 2).

daytime to perform automatic species recognition in the digital images based on the analyses of the RGB channels and texture features of same ROIs (Almeida et al., in press).

We did not detect within-species variations in Green% related to the position of the species crown in the image. However, for *P. torta* and some crowns of *Caryocar* in multiple positions differed in their daily Green%. These variations may be explained by modifications in leaf position due to wind, and also by individual specific attributes such as leaf angle inclination, type of leaf protection, and discolored leaves. Also, reflectance patterns of the leaves in different wavelengths may be considered (Ahrends et al., 2008; pers. obs.). In these cases, field observations will be important to combine image data processed with complementing observation of different trees and species.

4.2. Green patterns and on-the-ground phenology

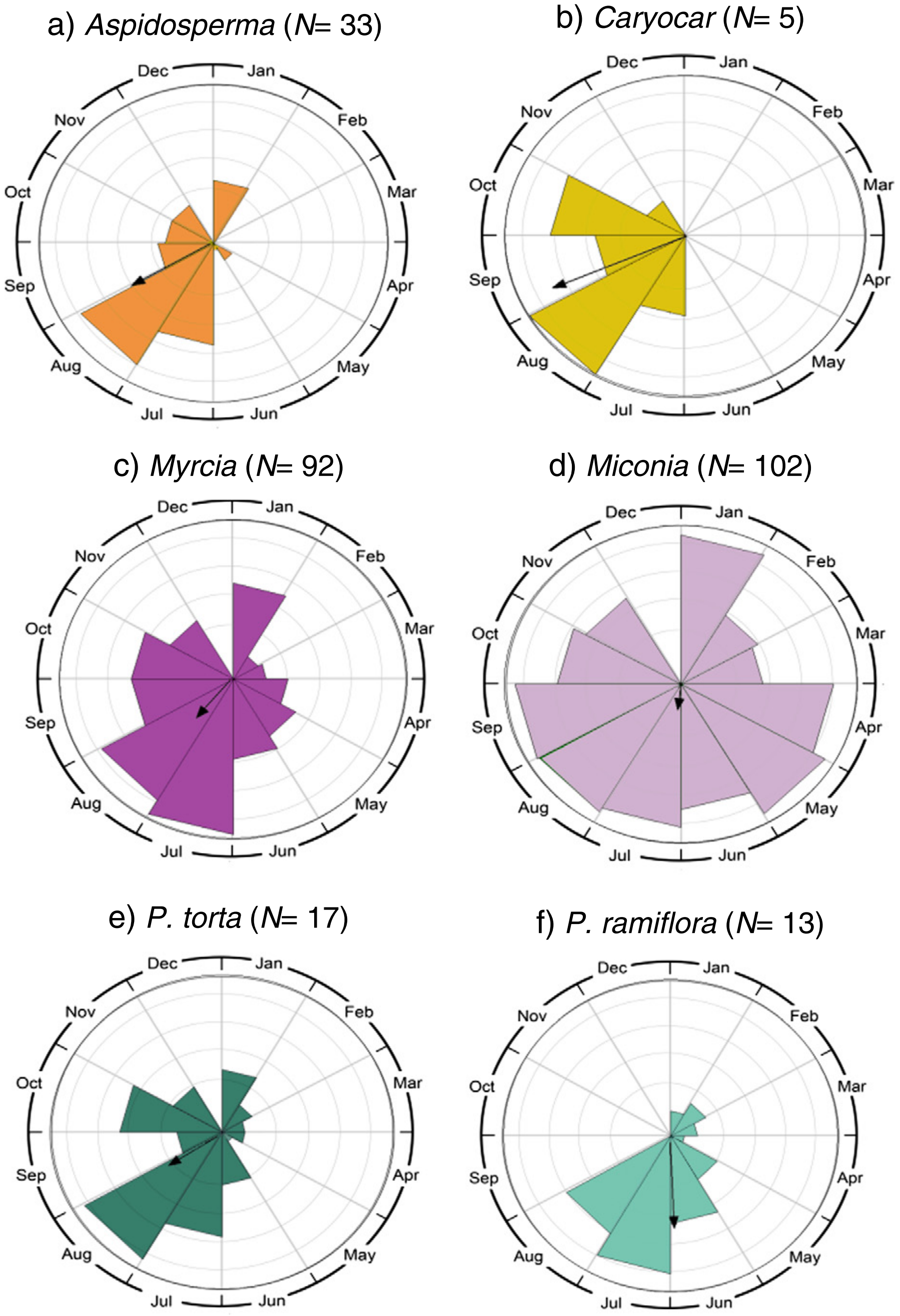
We verified leaf color changes along the main leafing season, in particular for each species' ROIs. The on-the-ground observations validated the phenological pattern derived from the digital images and also the species classification in the leafing functional groups: deciduous, semi-deciduous, and evergreen.

Cerrado community ROIs were not sensitive to changes in greenness within the time span analyzed here. Longer data series may be needed to perceive changes at the community level. ROIs integrating major parts of the community carry too much information, due to the high heterogeneity and diversity of tropical ecosystems (Woebbecke et al., 1995).

However, species' ROIs indicated distinctive leaf color changes, which allowed us to distinguish tree main leaf functional groups (deciduous, semi-deciduous, and evergreen species). Data from our on-the-ground local phenology was essential to identify the groups and validate the trends of greenness of the digital images' ROIs. Species with deciduous and evergreen leaf patterns typically differ in leaf life span (Van Ommen Kloeke et al., 2012). Deciduous trees usually have short leaf life span, and put out the new crop of leaves either just before the onset or in the beginning of the wet season in Southeastern Brazil and cerrado savannas (Lenza and Klink, 2006; Morellato et al., 1989; Rubim et al., 2010; Morellato et al. unpublished data). A decrease for the Green% values occurring in the peak of the leaf season was detected for evergreen and some semi-deciduous species, such as *Myrcia*, *Miconia* and *P. torta*. Those species may renew their foliage along the year or eventually during the dry season, when both, leaf flush and leaf fall, can proceed simultaneously (Lenza and Klink, 2006; Monasterio and Sarmiento, 1976; Rubim et al., 2010). Evergreen species keep the same foliage longer than deciduous species, but the color of the leaves changes during the leaf life span, with degradation of chlorophyll and different levels of carotenoids (Billow et al., 1994; Merzlyak et al., 1999). Moreover the Green% values also represent optical leaf color changes due to leaf maturity and aging processes (Richardson et al., 2009).

Although the three leaf functional groups as ecological strategies are very useful and largely applied to understand cerrado leaf change, this simplification leads to considerable loss of information (Petchey and Gaston, 2002). Single specimen can considerably vary in their flushing or greening pattern, for instance a single individual of *P. torta* increased in Green% whereas the average pattern based on four ROIs is clearly decreasing (Fig. 4 vs. Fig. 5) which also matches the on-the-ground observations based on 17 individuals (Fig. 6). In addition, single species inside those leaf functional groups differ in their mean greening pattern (see Fig. 5) and species belonging to different groups are not equally different.

Future research should use digital cameras images to explore cerrado savanna deciduousness as a continuous variable, by combining the analysis of green and red color channels, and the leaf color spectral changes over season.



a) *Aspidosperma* (*N*= 33)

b) *Caryocar* (*N*= 5)

c) *Myrcia* (*N*= 92)

d) *Miconia* (*N*= 102)

e) *P. torta* (*N*= 17)

f) *P. ramiflora* (*N*= 13)

Fig. 6. Circular histograms of the leaf flushing on-the-ground phenology during the year of study (2011) for the six species analyzed in the cerrado savanna study site, Southeastern Brazil. Frequency of individuals in the peak flushing of new leaves for (a) *Aspidosperma.*; (b) *Caryocar*; (c) *Miconia*; (d) *Myrcia* (e) *P. torta*; (f) *P. ramiflora*. The arrows point to the mean angle or date around with most individuals was flushing new leaves; the length of the arrow indicates the value of r, and represents the concentration of trees leafing around the mean date. The r has no units and varies from zero to one (when all the data are concentrated at the same direction or angle; see Methods for details). Within parentheses: number of trees observed on the ground.

5. Conclusions

This is the first study addressing the applicability of near-surface remote phenology to track leaf changes along the leafing season in tropical seasonal vegetation, the cerrado, and innovates by integrating on-the-ground validation by direct plant phenological observations. The digital camera turned out to be a reliable tool to monitor the phenology of cerrado savanna species; leaf functional groups were detected by analyses of the green channel, averaged over individual crowns' ROIs. Ground direct phenological observations were important to validate camera data and to develop a trustworthy methodology to be set up at new sites and in different ecosystems. There is a large range of ecological questions to be answered regarding leafing behavior (Polgar and Primack, 2011).

Near-surface monitoring systems in the tropics are necessarily complex since the environmental conditions are harsh and the diversity of species is usually high. The traditional method of the on-the-ground phenology, the direct observations of individual plants, preclude large spatial areas, human labor and the interference of the observer is high due to the inherent difficulties to detect the variations on leaf color patterns from leaf budding to senescence, especially in the tropics (Morellato et al., 2013; Morellato et al., 2010a; Morisette et al., 2009; Richardson et al., 2007). However, on-the-ground phenology is still the most widely applied method of observation in the tropics.

Additionally, it is a very confident technique to monitor individual based phenology and offers key information for validation of near-remote generated patterns. Image information from digital cameras is still sparse for high-diverse tropical vegetation, and allows us to obtain an impartial and comparable data of leaf seasonal changes. We consider that these two approaches are complementary to each other and the application will depend on the study goals. Near-surface remote phenology has becoming more and more common for phenological research and the arrivals of novel technologies followed by the advance of e-science methods for dealing with large data sets are changing the scenario of plant ecology studies.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecoinf.2013.12.011.

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