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Montes Claros, Minas Gerais

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Aos meus pais, Alfreu e Adelina, por nortearem o meu caminho até aqui, dedico.

"A natureza é o único livro que oferece um conteúdo valioso em todas as suas folhas."
Johann Goethe

Essa dissertação se encontra em formato de artigo científico a ser submetido à revista “Agricultural and Forest Meteorology”. Após as correções sugeridas pelos membros da banca, o artigo será formatado adequadamente seguindo as normas da revista.

UNIVERSIDADE ESTADUAL DE MONTES CLAROS
Centro de Ciências Biológicas e da Saúde
Departamento de Biologia Geral
Programa de Pós-Graduação em Ciências Biológicas

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Abstract

The aim of this study was to determine the K coefficient in different successional stages of a Brazilian Tropical Dry Forest (TDF): very early, early, intermediate and late. This coefficient was calculated according to the equation: K = logB/LAI, where logB was determined by values of NDVI (Normalized-Difference Vegetation Index) and EVI2 (Enhanced Vegetation Index) in different phenological phases of vegetation; and LAI (Leaf Area Index) was determined by the average of LAI at different phases of leaf development. The spectral indices (NDVI and EVI2) were derived from solar and photosynthetically active radiations measured by meteorological sensors. The LAI was obtained by using hemispherical photographs. Once the K coefficient is determined it can be applied to the equation: LAI= K*logB. Due to TDF seasonality, the LAI, NDVI and EVI2 varied significantly throughout the rainy season. The measured indices varied significantly between successional stages, indicating sensitivity to structural differences during forest regeneration. Due to variations during the leaf development in TDF, we also determined ΔK (leaf growth phase) and Kmax (leaves fully expanded). Furthermore, the K values differed between succession stages. Thus, we established a model based on spectral properties of vegetation coupled with biophysical characteristics in a TDF that makes possible to estimate LAI. The application of the K coefficient can improve remote estimations of forest primary productivity and gases and energy exchanges between vegetation and atmosphere.

Keywords: spectral vegetation indices, leaf area, remote monitoring, tropical dry forest, successional stages, phenology.

Resumo

O objetivo desse estudo foi determinar o coeficiente K em diferentes estágios de sucessão de uma Floresta Tropical Seca (FTS) brasileira: muito inicial, inicial, intermediário e tardio. Esse coeficiente foi calculado de acordo com a equação: K= logB/IAF, em que logB é determinado por valores de NDVI (Índice de Vegetação por Diferença Normalizada) e EVI2 (Índice de Vegetação Aprimorado) em diferentes fases fenológicas da vegetação; e o IAF (Índice de Área Foliar) é determinado pela média de IAF em diferentes fases de desenvolvimento foliar. Os índices espectrais (NDVI e EVI2) foram derivados a partir da radiação solar e fotossinteticamente ativa mensuradas por sensores meteorológicos comuns. O IAF foi obtido através da técnica de fotografias hemisféricas. Uma vez determinado o coeficiente K ele pode ser aplicado na equação: IAF= -K*logB. Devido à sazonalidade da FTS, os valores de IAF, NDVI e EVI2 variaram significativamente ao longo da estação chuvosa. Os índices mensurados variaram significativamente entres estágios sucessionais, indicando sensibilidade às diferenças estruturais dos estágios. Devido às variações em decorrência do desenvolvimento foliar na FTS, foram determinados também o ΔK (fase de crescimento foliar) e Kmax (folhas já completamente desenvolvidas). Além disso, os valores de K variaram entre estágios sucessionais. Assim, estabelecemos um modelo, baseado em propriedades espectrais da vegetação aliado às características biofísicas de uma FTS, através do é possível estimar o IAF. A aplicação do coeficiente K pode ainda aprimorar estimativas remotas de produtividade primária florestal e as trocas de gases e energia entre vegetação e atmosfera.

Palavras-chave: índices espectrais da vegetação, área foliar, monitoramento remoto, floresta tropical seca, estágios sucessionais, fenologia.

1. Introduction

The energy, water and carbon exchange between vegetation and atmosphere can be influenced by the forest biomass amount, which is indirectly indicated by the plant canopy height and leaf area, among other parameters (Campbell & Norman, 1998; Asner et al. 2003; Wilson & Meyers, 2007). Determining the contribution of vegetation to matter exchange flows in the atmosphere depends on monitoring phenological processes such as leaf development: emerging leaves, growing, expansion, maturation and abscission (Campbell & Norman, 1998; Wilson & Meyers, 2007). Spectral vegetation indices (IVs) consist in a useful tool to monitor such phenophases (Asner et al. 1998; Pettorelli, 2005). IVs are obtained through combinations of different types of measurements of leaf radiation reflectance (Campbell & Norman, 1998; Kalácska et al. 2004a), which are sensitive to combined effects of the chlorophyll concentration, leaf area, leaf clumping and plant canopy architecture (Turner et al. 1999).

The Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI2) (Wilson & Meyers, 2007; Rocha & Shaver, 2009) are examples of VIs that have been widely used in studies on vegetation monitoring due to their strong correlation with plant biomass (Carlson & Ripley, 1997; Turner et al. 1999). The NDVI is determined by the amount of incident near infrared (NIR) and visible (VIS) radiations, comprising the range of photosynthetically active radiation (PAR), with the former being strongly reflected or transmitted and the latter strongly absorbed by the plant canopy (Carlson & Ripley, 1997; Campbell & Norman, 1998). The EVI is obtained by the same way as the NDVI, but a correction factor is used to reduce the interference of atmospheric and soil factors (Rocha & Shaver, 2009). Both indices have a range of variation between -1 and 1: values closer to

1 indicates that there was a higher NIR reflectance and higher VIS absorption (Kalácska et al. 2004a), which can probably be associated with a larger biomass amount (Campbell & Norman, 1998; Kalácska et al. 2004a).

Despite having a good relationship with biomass amount, IVs do not provide quantitative information about biological or environmental factors contributing to the PAR absorption, such as leaf area and/or chlorophyll content (Jacquemoud, 1992; Asner, 1998; Campbell & Norman, 1998). However, IVs have shown a good correlation with the Leaf Area Index (LAI), defined as half the total leaf surface area per unit of horizontal surface (Asner, 2003; Yang, 2006) The LAI is useful to indirectly estimate forest productivity and has been widely used in ecological monitoring and environmental conservation studies (Carlson & Ripley, 1997). The leaf area is one of the main regulators of microclimatic conditions within and below the plant canopy, controlling water interception, carbon exchange and solar radiation absorption and transmission (Bonan, 1995; Breda, 2003; Fournier et al. 2003; Van Wijk & Williams, 2005; Clark, 2008). Since the vegetation is dominated by leaves, where most chlorophyll is stored (Fournier et al. 2003), we can then consider that the LAI is useful for estimating forest photosynthetic rate (Gonsamo, 2009). Thus, LAI changes in the plant canopy, either by natural or anthropogenic effects, result in changes in forest primary productivity (Breda, 2003).

The LAI can be obtained by indirect measurements through optical devices, based on solar radiation amount that reaches both the canopy and the understory (i.e., LAI-2000, plant canopy analyzer, LI-COR®) or by estimating leaf amount on the canopy, based on pixel analyses from hemispherical photographs (White et al, 2000; Asner, 2003; Fournier et al, 2003). Although it is a very useful tool in environmental monitoring, to obtain reliable

LAI data requires training and several incursions into the field (Carlson & Ripley, 1997; Manninen et al, 2005). However, the strong correlation between LAI and IVs is an incentive to create models based on spectral indices characterizing vegetation (Wilson & Meyers, 2007). In this context, Wilson and Meyers (2007) proposed an equation with which is possible to obtain LAI using NDVI data based on photosynthetically active and solar radiations measured by flux towers, using a coefficient which they named as *K*. Thus, since NDVI and LAI data are obtained, it is possible to obtain the K value, to further apply in the equation established by Wilson & Meyers (2007) and estimate the LAI automatically.

Once these models are successfully established and tested, the monitoring of endangered forests, such as the Tropical Dry Forests (TDFs) (sensu Sanchez et al. 2005), would be automated, with lower costs and higher efficiency. The highest deforestation rates of TDFs were recorded for South America between 1980 and 2000 (Miles et al. 2006). As a rule for the tropics, land use and further abandonment turned this vegetation type into vegetation mosaics in different stages of natural regeneration (Arroyo-Mora et al. 2005). As the structure and function (i.e., productivity, water balance, nutrient cycling, among others) of these secondary TDFs varies with forest age, it is likely that successional stages can be remotely differentiated via satellite imagery (Gallardo-Cruz et al. 2012). Therefore, improving remote sensing techniques focused in TDF natural regeneration can provide useful information to policy-makers and support the development of policies for environmental monitoring, management and sustainable use in this ecosystem (Espírito-Santo et al. 2006; Quesada et al. 2009).

The present study aimed to determine the K coefficient for different successional stages in a Brazilian TDF, through the relationship between LAI and IVs. Specifically, we intend to answer the following question: Does the K coefficient changes as a function of leaf development (as indicated by LAI) and successional stage?

2. Methods

2.1. Study area

This study was conducted in the Mata Seca State Park (MSSP), created by the expropriation of four farms, with an area about 15.281.44 ha, under the Instituto Estadual de Florestas responsibility (IEF, 2000). The MSSP is located in the valley of the San Francisco River (14°48'36"-14°56'59"S and 43°55'12"-44°04'12"W), in Manga, Minas Gerais. It has a semi-arid tropical climate according to the Köppen’s classification (modified by Peel, 2007), characterized by a well-defined dry season. Average temperature in this region is 24 °C, with an average annual precipitation of 871 mm (Antunes, 1994). The MSSP is mainly covered by deciduous vegetation (TDFs sensu Sanchez-Azofeifa et al. 2005), with approximately 90-95% leaf loss during the dry season (May-October) (Pezzini et al. 2008, 2014). Due to the historical land use, i.e. agriculture and pasture (Table 1), the park TDFs form a mosaic in different successional stages (Madeira et al. 2009), defined here as very early, early, intermediate and late (Table 1).

2.2. Sampling design

2.2.1 Obtaining the Spectral Vegetation Indices (NDVI and EVI2)

In each one of the four successional stages, one tower with a set of radiation sensors was assembled from 2007 to 2012. For this study we consider only data from August 2012 (dry season) to June (end of wet season). Two pyranometers (Onset®- LIA and LIB) (PYR, measuring the solar radiation flux density) and two PAR (Onset®- LIA and LIB) sensors (measuring the radiation between 400 and 700 nm) were installed per tower. Tower extension depends on the canopy height, in such a way that sensors are always positioned at 5 m above the canopy. Each group of four sensors had a pair of PYR-PAR sensors facing up and down to measure the incoming and outgoing radiation, respectively. The field-of-view of the sensors is around 10 meters in radius. These sensors measure the incoming and radiation at 30 seconds intervals throughout the year, logging (loggers, Onset®) at every 30 minutes. To our study only the measurements obtained between 10 and 14 hours were considered, because in this period the radiation fluxes measured by the sensors above the canopy receives less inference of bidirectional reflectance distribution function (BRDF), due the solar zenith angle corresponding to less than 30° (Disney, 2004). With these radiation measures (near infrared-R_{nir} and visible-R_{vis}), we can calculate NDVI and EVI2 according to the following equations (Campbell & Norman, 1998; Rocha & Shaver, 2009):

$$NDVI = R_{nir}-R_{vis}/R_{nir} + R_{vis}$$

$$EVI2 = 2.5\ R_{nir}-R_{red}/R_{nir}+^{2.4}R_{red}+1$$

2.2.2. Obtaining the Leaf Area Index (LAI)

We delimited a plot of 20m x 20m surrounding each tower (with the tower in the center of this quadrat) and established sampling points of LAI within the field-of-view limit

(10 m) of PAR and PYR sensors (Figure 1), totaling 24 sampling points in each successional stage (Figure 1). We considered three phases of leaf development and used hemispherical photographs to record them. The phases considered in this study were referred as growth, fully expanded and senescent. First, we obtained hemispherical photographs in September 2012, when trees are leafless, to calculate the Wood Area Index (WAI). With the onset of the rainy season, new leaves were produced in the first half of November 2012. We took hemispherical photographs in a daily basis to obtain Plant Area Index (PAI) throughout the phase of leaf expansion, from November 12th to 25th. After this period, leaves were fully developed and expanded, and this new phase lasted from December to March, when we conducted six samplings of hemispherical photographs at approximately 20 days intervals. With the onset of the dry season, leaf senescence started and lasted from April to June. During this phase, we conducted monthly PAI measurements, until complete leaf abscission was observed. Finally, we calculated the specific Leaf Area Index (LAI) by removing the contribution of WAI from PAI values (Kalácska et al. 2005a).

Photographs were taken using a camera (Pentax- SR) with a 180º lens (fish-eye) focused to the sky at a height of 1.30 m above the forest floor, under conditions of diffuse light during sunrise or sunset, or in cloudy days to prevent direct incidence of sunlight on the hemispherical lens. These photographs produce circular images that record the size, shape and location of gaps in the forest canopy. Such images were converted to bitmaps and analyzed using the Hemispherical Photo Analyser (HPA) software (Opie, 2010). Image processing involves transforming positions of image pixels in angular coordinates, dividing the intensity of the pixels in the classes representing the sky and the area that represents the vegetation, and the computation of the distribution of the brightness of the sky (Opie, 2010).

2.2.3. Calculation of the coefficient K

After obtaining the IVs and the LAI, all indices were applied to the following equation:

$$(a)\ LAI = -K * \log B$$

Where B is given by: $(NDVI_{max}-NDVI_{i})/(NDVI_{max}-NDVI_{min})$; $NDVI_{max}$ corresponds to the average of NDVI values when the vegetation is dense; $NDVI_{min}$ is the average of NDVI minimum values when there is little or no contribution of leaves to the absorption or reflectance of the radiation; and $NDVI_{i}$ is the mean of all changes in NDVI values during the rainy season. The LAI value is determined by the average all sampling points in a given plot. The value of the K coefficient was then determined for each sampling date by rearranging the equation (a):

$$(b)\ K = \log B / LAI$$

During the leaf growth phase, the K coefficient values vary with leaf biomass increase. We calculated such variation (ΔK) as the slope of the straight-line equation obtained from a linear regression analysis, with the K value as a function of time (in days) of the growth phase. We also calculated the average maximum value of the K coefficient (K_{max}), using the measurements taken during the “fully-expanded leaves” phase, when the K values showed less variation.

2.3. Statistical analyzes

We performed a regression analyses to assess the degree of correlation between the LAI and each IV. These analyses were performed as a pre-requirement to calculate the K coefficient. If there were no significant correlations between the LAI and the IVs, the determination of the K coefficient from LAI values would not be valid.

To compare LAI and PAI among successional stage and phenophases, we constructed linear mixed effect models (LME), since the measurements were taken repeatedly through time in the same sampling points, which violates the assumption of sampling independence. LAI and PAI were used as independent variables (fixed effects), whereas the date which the data were collected were assumed as random effects. After the construction of LME, we performed an analysis of variance (ANOVA), followed by contrast analysis, to test the difference between LAI and PAI means in different successional stages and phenophases. We conducted all analyzes in the software R 2.11 (R Development Core Team, 2010). All values are given as mean ± standard error.

3. Results

3.1. Temporal and successional variations in vegetation indices

The mean values of the spectral indices varied according to the seasonality and the successional stages (Tables 2 and 3). Furthermore, the minimum and maximum values of both VIs showed different patterns for each stage. The minimum NDVI values showed the lowest mean for the late stage and highest for the early stage. The maximum NDVI values were also observed for the early stage, however the lowest corresponded to very early stage. The highest $NDVI_i$ over the rainy season was observed with the late stage, whereas the lowest variation was recorded in the very early stage (Table 2). Regarding the EVI, the intermediate stage presented the lowest EVI_{min}, EVI_{max} and EVI_i values. The late stage showed the highest values of EVI_{min} and EVI_i and the highest value of EVI_{max} was recorded in the early stage (Table 3). Finally, the value of logB, based on EVI and NDVI was higher in late stage and lower in the early stage (Tables 2 and 3).

The indices used in this study (LAI and PAI) to estimate plant biomass and assess the leaf development showed large variations over the study period for all successional stages (Figs. 2A e B). In general, both indices indicated a synchronous pattern of leaf production, development and expansion, as well as of leaf abscission. As a whole, both PAI and LAI differed between the phenophases here considered ($p<0.01$) (Table 4). The lowest values of both indices were observed for the growth phase and highest values for the fully expanded phase in all stages (Figs. 2A e B).

PAI and LAI also differed between successional stages along the phenophases. During the growth phase, the intermediate stage showed the highest PAI, but when the leaves were completely expanded, the greatest PAI was observed for the early stage, followed by late stage. In the senescence phase, leaf abscission occurred more slowly in the intermediate stage, whereas the other stages exhibited a sharp drop in PAI values (Figure 2A).

For LAI values, the between-stage temporal variation was different from the observed for PAI, with the early stage showing highest values during the growth phase. This pattern remained in the fully-expanded phase. During senescence, the same successional pattern observed for PAI values was recorded for LAI: the intermediate stage had slower leaf loss, whereas the other stages showed an abrupt decline in LAI values (Figure 2B).

3.2. Determination of the K coefficient

The spectral vegetation indices showed a significant relationship with leaf area index. Thus, the observed variation in the values of IVs (NDVI and EVI) can be explained by seasonal variation in LAI (Figure 3). The K coefficient varied as a function of time and as a function of the succession gradient. The temporal variation of the K coefficient shows the same trend in all successional stages, being more variable in the growth phase and more stable in the fully-expanded phase (Fig. 4). The differentiation among stages occurred only on the quantity and leaf area. The greater variation in the coefficient K is represented by ΔK, which corresponds to the range of leaf growth. The lower variation is represented by Kmax and corresponds to the fully-expanded phase. The K_{max} and ΔK were both higher in the early stage and lower for the late stage (Tables 2 and 3), reflecting a negative relationship with logB, since stages with the higher values of logB has smaller values of K (Tables 2 and 3).

4- Discussion

In general, the basic goal of the present study was achieved, since our results demonstrated that common meteorological sensors measuring fluxes of solar and photosynthetically active radiation can provide reliable data for NDVI and EVI that correlated strongly with a biophysical parameter (LAI) in a Brazilian TDF. We also showed how such K correlation coefficient vary in time and how it differs between successional stages, a first step to provide more reliable tools for TDF monitoring using remote sensing techniques.

4.1. Temporal and successional variations in vegetation indices

TDF are highly seasonal ecosystems, with a short rainy season (4-6 months) when leaves are produced and lost very quickly (Lopezaraiza-Mikel et al. 2013). Such sharp variations were expressed in the NDVI and EVI obtained in the present study, and besides the obvious changes in in leaf number and size during the rainy season, the VIs may also reflect differences in pigment concentration along these phenophases. Such patterns are visible in distinct shades of green of the leaves, resulting in a change in reflectance values (Hesketh & Sanchez-Azofeifa, 2013).

Besides the sensitivity to forest phenology, is also important to highlight the sensitivity of VIs to the forest structural changes along the successional gradient. As the structure and function of these secondary TDFs varies with forest age (Gallardo-Cruz et al. 2012), VIs sensitivity to structural changes indicate their usefulness to distinguish stages of natural regeneration. This is one of the first studies demonstrating the utility of EVI2 to such purpose. Regarding NDVI, this study adds to other studies that have shown satisfactory results with the application of NDVI for the differentiation of stages in secondary forests (Arroyo-Mora et al. 2005; Gallardo-Cruz et al. 2012).

Although the maximum values of NDVI and EVI have been higher in the early stage, their overall variation during the rainy season was higher in the late stage. This suggests an overestimation of the spectral indices in the early stage, associated to the fact that the higher canopy openness at this stage leaves the soil more exposed, affecting the type of radiation that is reflected to the sensors (Kaláksca et al. 2005b). The early stage forest grows on dark red latosol, with the upper surface horizon characterized as dark red-gray coloration. Darker soils also absorb radiation in the visible range, reducing the amount of radiation that will be sent to the sensors. As NDVI and EVI are based on the difference between R_{nir} and R_{vis}, the reduction in reflectance values results in increased values of both spectral indices (Campbell & Norman, 1998).

The differences in PAI and LAI in the phases of development also reflect the strong seasonality of the studied TDF. Furthermore, we observed differences in the values of PAI and LAI among very early and intermediate (which did not differ between them), early and late stages, probably due to differences in vertical canopy structure (Kalácska et al. 2005b), indicating the utility of these indices to discriminate TDF successional stages (Kalácska et al. 2005b). The highest average of PAI in the intermediate stage during the growth phase can be attributed to the greater contribution of the wood area index (WAI) in this stage (Sanchez-Azofeifa et al. 2009). At the MSSP the intermediate stage is characterized by the abundant presence of lianas (Sanchez-Azofeifa et al. 2009), increasing its wood volume compared to other stages. However, LAI did not differ between the intermediate and the very early stage, indicating that the leaf contribution of lianas is not as expressive. The late stage showed the lowest values of PAI and LAI along the growth phenophase, probably due to a slight lack of synchrony in leaf flushing between its two well-defined vertical strata, with canopy greening occuring after the understory.

In the fully-expanded phase, except for the early stage, the PAI and LAI increased with succession (very early < intermediate < late). Contrary to the expected, the early stage had the highest PAI and LAI, although structural variables in the MSSP have been shown to increase along the successional gradient (Madeira et al. 2009, Espírito-Santo et al. 2013). This may be associated with a possible LAI overestimation due to the height where hemispherical photographs were obtained (1.30m), which is very close to the understory in the early stage.

In the senescence phenophase, values of PAI and LAI showed a sharp decrease for all except the intermediate stage. Kalácska et al (2005a) also observed a similar pattern in the leaf fall at the intermediate stage compared to other successional stages of a TDF in Costa Rica. Leaf lifespan is a result of plant responses to light, nutrient and water availability, among other biotic and abiotic factors (Reich et al. 1992). The intermediate stage forest is located on a relatively poorer soil, where nutrient levels, base saturation and cation exchange capacity are significantly lower (Espírito-Santo et al. 2013). Thus, it is possible that the cost of leaf production is higher in this stage, resulting in a slower leaf abscission and more efficient use of nutrients.

4.2. Determination of the K coefficient

The strong correlation between spectral vegetation indices (NDVI and EVI) and LAI demonstrates that it is possible to obtain the LAI accurately based on NDVI and EVI data. This is one of the first studies showing the good correlation existing between EVI2 with LAI. Regarding the relationship between NDVI and LAI, the value of R^2 found here is close to that found by Kalácska and co-workers (2004a) in a Costa Rican Tropical Forest. VIs such as NDVI are sensitive to different ranges of LAI and could saturate asymptotically in vegetation types with LAI above 5 (Kalácska et al. 2004a). In the present TDF, the greatest value of LAI was below 3, so the NDVI might be considered adequate to detect variations in LAI for this ecosystem. Thus, the coefficient K determined in this study, based on NDVI, EVI2 and LAI, is likely a reliable way to monitor the production of biomass in different successional stages in a TDF, although further validation is necessary.

The greatest variation of NDVI and EVI throughout the rainy season in the late stage resulted in a higher value for the value of logB at the same stage. Thus, a negative relationship between logB and the coefficient K was observed. This indicates that with the advance of the ecological succession, the value of K decreases. Wilson & Meyers (2007) found a different pattern, with a positive spatial relationship between LAI and the K coefficient. This difference in patterns may be explained by the different methods for obtaining LAI, since those authors used LAI products from MODIS ASCII and our study used LAI based on ground-measurements.

Because our study area is a strongly seasonal TDF, the growth phase is short and extremely variable, followed by an apparent stability in the fully-expanded phase. We considered that it would be unreliable to define a single K coefficient to estimate the LAI for the whole phase of leaf development throughout the rainy season. Thus, our study is innovative not only for defining the K coefficient for different successional stages in a TDF, but also for indicating that, in seasonal ecosystems, the K coefficient should be defined by ΔK and K_{max} in order to obtain more reliable values of LAI for each one of the different phenological phases.

The K coefficient also varied along the successional gradient, indicating its usefulness in monitoring studies in secondary forests. Once the K coefficient is validated, it could be used to obtain accurate and automated LAI. Access to this variable enables the remote differentiation of successional stages and consists in an important approach for the management and conservation of Brazilian TDFs. Taking into account that Brazilian laws restrict the clearing of more advanced areas of regeneration, we can provide to policy-makers a new tool to improve the effective enforcement of environmental laws (Espírito-Santo et al. 2013).

Conclusion

Our study is the pioneer in the attempt to determine a K coefficient that estimates LAI in different successional stages of a TDF accurately and efficiently. The reliability of this coefficient is high, since it was based on direct (LAI) and indirect (NDVI and EVI) biomass predictors highly correlated. The daily monitoring performed by *in-situ* meteorological sensors in real time provides consistent NDVI and EVI data from which we can now obtain more reliable measures of LAI. The potential use of the K coefficient is enormous, representing an advance in the estimation of forest primary productivity, gas exchange and energy between vegetation and atmosphere. However, validation of this coefficient by spatial replication in other regions is necessary and will be conducted in future studies.

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Table 1. List characterizing vegetation structure and land use history at MSSP.

Stages	Forest structure	Land use history
Very Early (VE)	Presence of patches of sparse vegetation, canopy reaching 5 m in height, and an understory consisting of an herbaceous-shrub stratum.	This area was used as pasture for about 20 years and abandoned in 2000, but was used occasionally by free-ranging cattle until 2006.
Early (E)	Presence of patches of sparse vegetation, canopy reaching 7 m in height, and an understory consisting of an herbaceous-shrub stratum.	This area was used as pasture for about 20 years and abandoned in 1990. Forest regeneration occurred mainly through tree resprouting.
Intermediate (I)	Presence of two vegetation layers: a canopy stratum ranging from 8 m with some emergent trees over 15 m, and a dense tree-shrub layer consisting of young trees and abundant lianas.	This area suffered clear-cut in the past, but is under regeneration since the 1960s with the occasional occurrence of free-ranging cattle until 2006.
Late (L)	Presence of two well-defined strata: a tree stratum with a closed canopy is composed of trees with heights between 10-12 m, with some emergent trees over 18 m and a sparse shrub layer with low density of saplings and lianas.	There are no records of clear-cutting in this area, but low-intensity, occasional selective logging and sparse free-ranging cattle occurred until the 2006.

Table 2. The stage-based maximum, minimum and seasonal changes on NDVI ($NDVI_{max}$, $NDVI_{min}$ and NDVIi) used to find the K value for two phenophases: fully expanded leaves (Kmax) and leaf growth (ΔK).

Stage	$NDVI_{min}$	$NDVI_{max}$	NDVIi	logB	K max	ΔK
Very Early	0.541	0.796	0.696	0.407	3.09	0.183
Early	0.574	0.881	0.744	0.349	5.87	0.329
Intermediate	0.553	0.846	0.715	0.349	3.72	0.235
Late	0.533	0.846	0.778	0.662	2.76	0.135

Table 3. The stage-based maximum, minimum and seasonal changes on EVI (EVI_{max}, EVI_{min} and EVIi) used to find the K value for two phenophases: fully expanded leaves (Kmax) and the leaf growth (ΔK).

Stage	EVI_{min}	EVI_{max}	EVIi	logB	K max	ΔK
Very Early	0.280	0.574	0.445	0.359	3.403	0.208
Early	0.274	0.693	0.481	0.296	6.93	0.388
Intermediate	0.272	0.536	0.406	0.310	4.18	0.265
Late	0.292	0.629	0.525	0.513	3.56	0.175

Table 4. Summary statistics for LAI and PAI in the different successional stages and in the different phenophases.

Response variable	Explanatory variable	DF	F-value	p-value
LAI	Stage	3	6.482	<0.0001
	Phenophase	2	756.172	<0.0001
	Stage:Phenophase	6	29.479	<0.0001
PAI	Stage	3	3.365	<0.05
	Phenophase	2	808.607	<0.0001
	Stage:Phenophase	6	26.1736	<0.0001

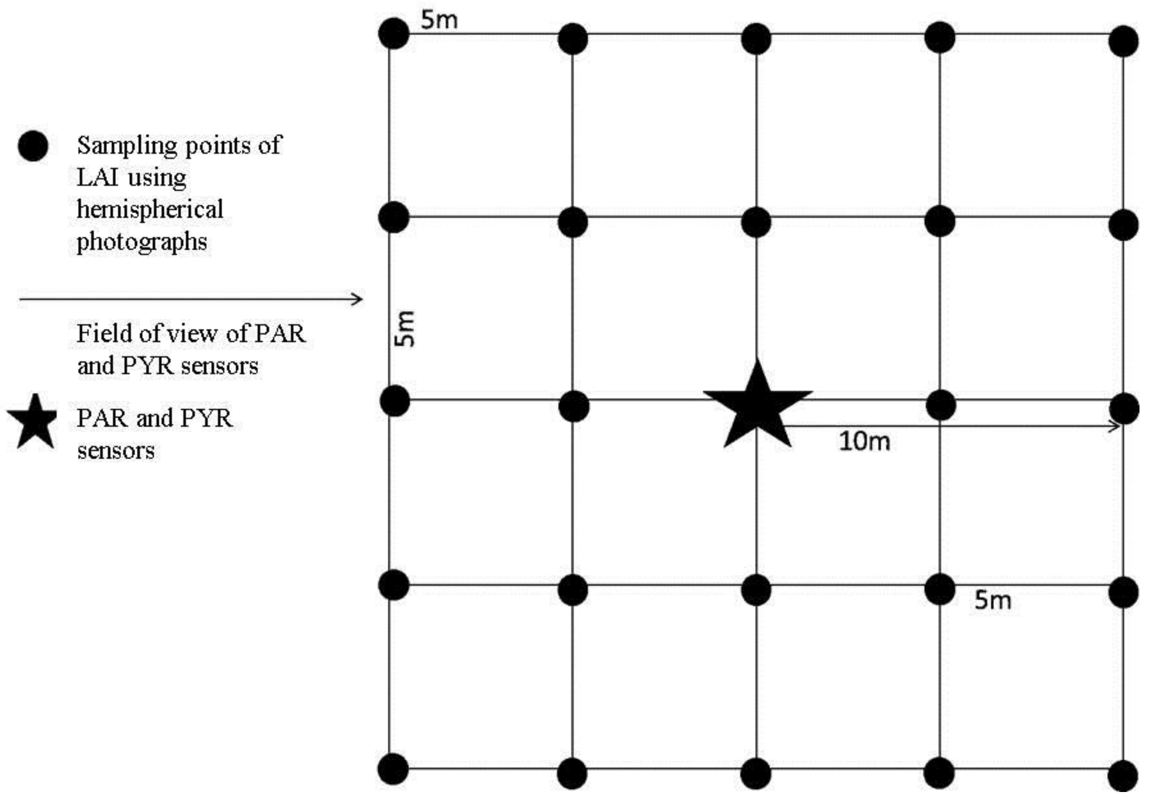

Figure 1. Sampling points of LAI within the field-of-view limit (10 m) of PAR and PYR sensors.

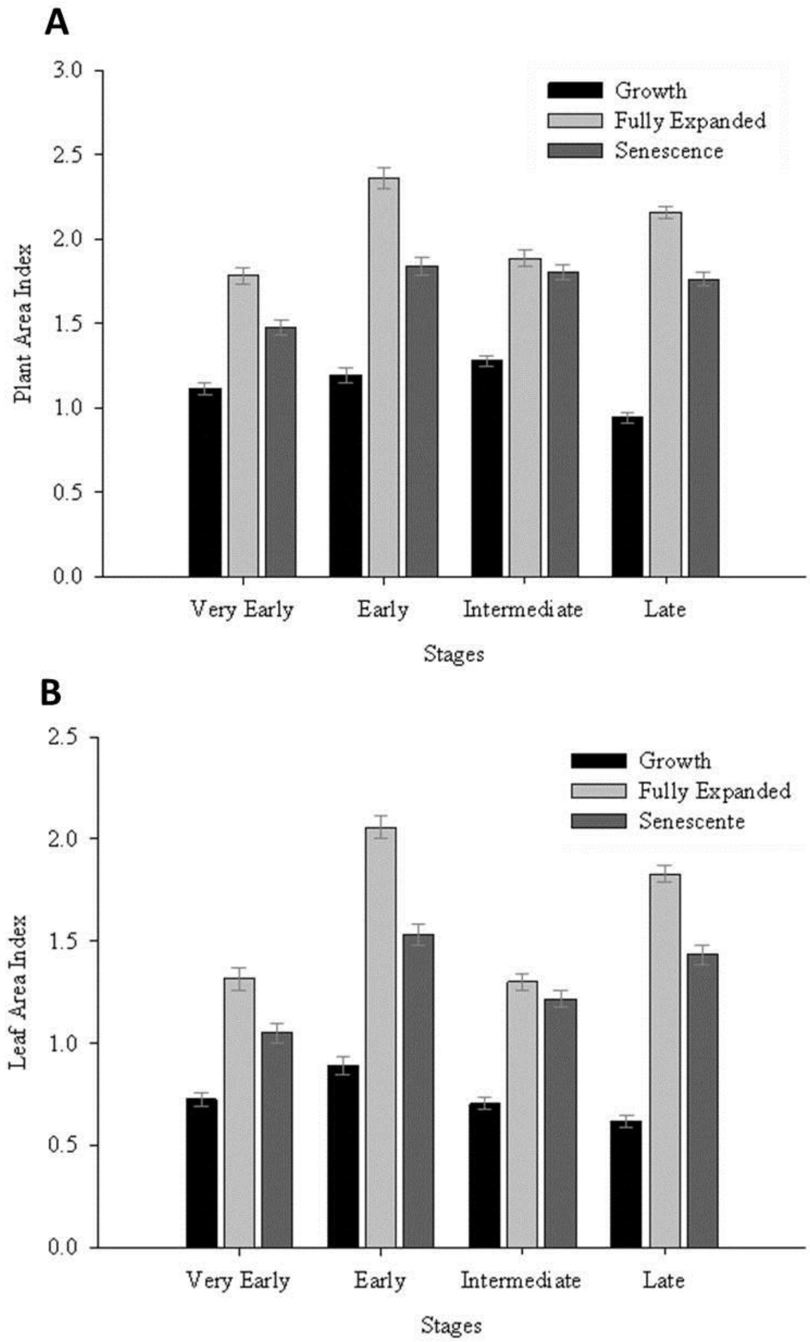

Figure 2. A- Plant area index in the very early, early, intermediate and late successional stages in the different phenophases. B- Leaf area index in the very early, early, intermediate and late successional stages in the different phenophases.

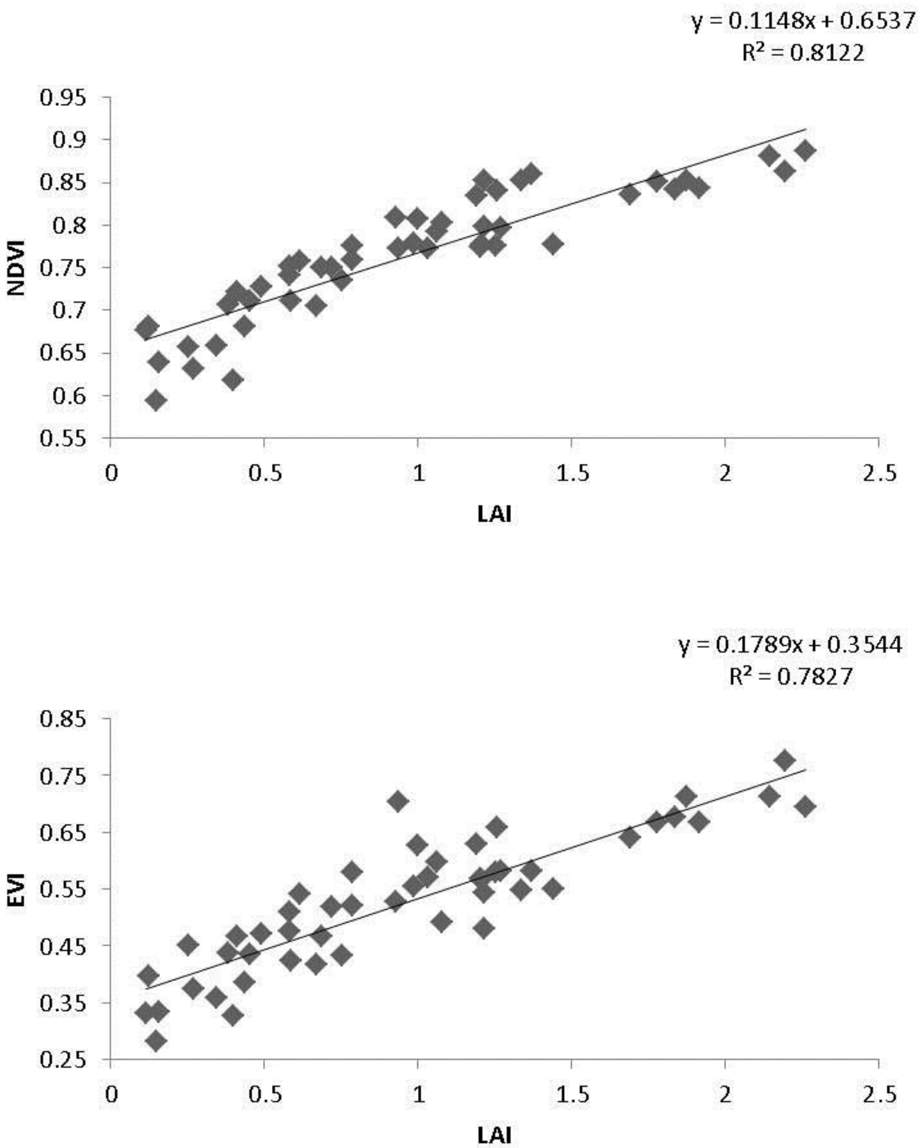

Figure 3. Correlation between LAI and Vis for all stages during all growth and fully-expanded leaves phases in a tropical dry forest.

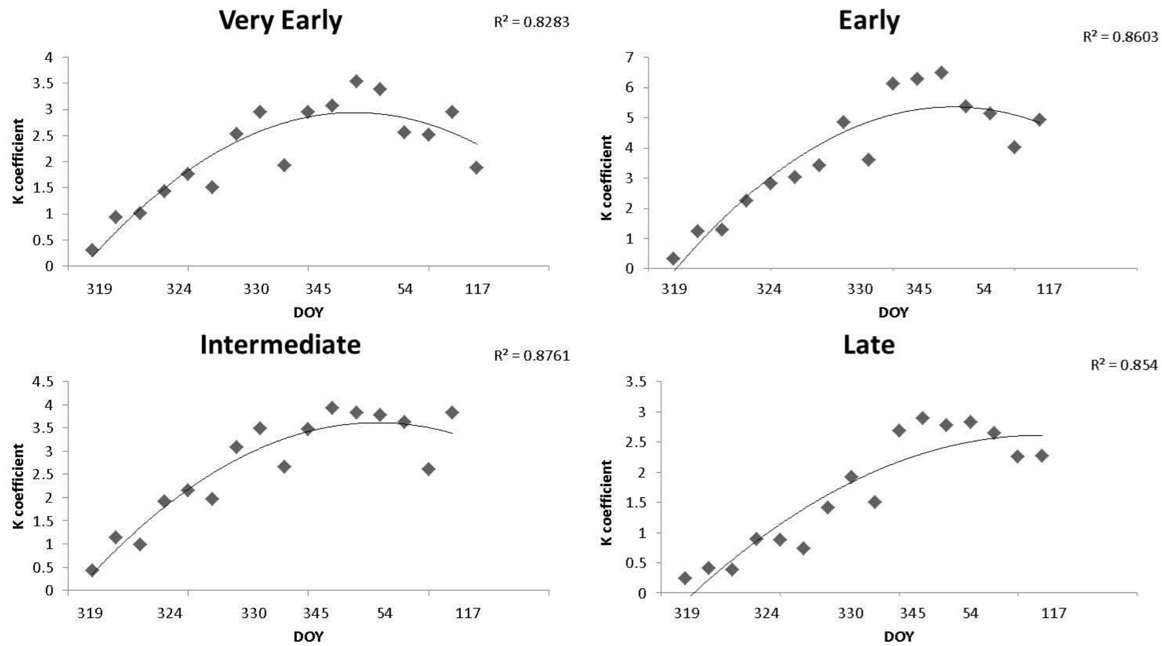

Figure 4. K coefficient variation during leaf growth phase and the fully-expanded leaves phases. DOY = Day of the Year.