University of Alberta

Evaluation of MODIS-LAI products in the tropical dry secondary forest of Mata Seca, Minas Gerais, Brazil

by

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ABSTRACT

Leaf Area Index (LAI) advances scientific knowledge of the role of secondary forests in forest area conservation. MODIS-LAI products provide an alternative, efficient and cost-effective method for measuring LAI in Tropical Dry Forests (TDFs). The performance of MODIS-LAI satellite products in a TDF was studied as a function of successional stages by (1) estimating seasonal LAI variations compared to *in situ* LAI values (2) using dry season MODIS-LAI products to estimate Woody Area Index (WAI) (3) estimating phenology changes through comparisons to *in situ* data. The study demonstrates (1) MODIS-LAI product showed agreement with *in situ* values with increasing successional stage. (2) MODIS-LAI product showed best agreement to *in situ* WAI values in the intermediate successional stage. (3) TIMESAT analysis indicated that MODIS-LAI products detected start-of-season 1-2 weeks before *in situ* values and end-of-season 20-30 days after *in situ* values, indicating that MODIS-LAI product captures canopy leafing, but is not suitable for detecting senescence.

Keywords: Leaf Area Index, Validation, MODIS, Woody Area Index, Phenology, Tropical Secondary Forest Succession, Hemispherical Photography, LAI-2000,

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1. INTRODUCTION

1.1 Importance of tropical forests

Although most of the world's land mass is located in the Northern Hemisphere, an important area of the world lies in the region between 15º and 25º N and S: tropical forests (Köeppen Climate Classification System). Tropical forests are the most biologically diverse ecosystems on earth (Lewis *et al.* 2009; Quesada *et al.* 2009); maintaining a crucial role in an ecosystem by providing many services to humans such as biodiversity conservation (Downton 1995, Kalácska *et al.* 2004; Lewis *et al.* 2009), water production, water balance control (Downton 1995, Kalácska *et al*. 2004) and deterring desertification of soils and soil erosion (Kalácska *et al.* 2004; Myers 1988). In addition to cycling nutrients, mitigating weather disasters (Kalácska *et al.* 2004), promoting cloud formation and regional rainfall (Lewis *et al.* 2009), and by processing, storing and exchanging carbon through photosynthesis (Downton 1995; Kalácska *et al.* 2005a; Lewis *et al.* 2009).

1.2 Threats to tropical dry forests

Covering a small percentage of the world's land mass, tropical dry forests (TDFs) are one of the most threatened tropical ecosystems of all major tropical forest types (Madeira *et al.* 2009; Miles *et al.* 2006). Past and present rates of TDF conversion indicate that most mature tropical forests will disappear in the near future; leaving only pasture lands and forest patches under varying degrees of succession (Quesada *et al.* 2009). Higher rates of forest loss and degradation are more prominent in tropical countries containing TDFs than in tropical rainforests (Miles *et al.* 2006; Quesada *et al.* 2009).

TDF health is being threatened due to human settlement because of their fertile and flat landscapes, which are optimal places for agricultural development resulting in slash-and-burn practices (Kalácska *et al.* 2005b, Madeira *et al.* 2009 Quesada *et al.* 2009). In addition, TDFs are the most desirable for economic development practices, the most extensively used, and the least conserved of tropical ecosystems (Sánchez-Azofeifa *et al*. 2003, 2005). Changes in land use and abandonment of agricultural lands have increased the number of secondary forests in the tropics (Crk *et al*. 2009). Indeed, between 1980 and 2000, TDFs have disappeared yearly in the Americas at a rate of 0.6% (Madeira *et al.* 2009). Additional threats to TDF's include climate change, habitat fragmentation and human population increases (Madeira *et al.* 2009). TDFs tend to be more susceptible to disturbance because of their slow growth due to the short growing seasons. As a result, regeneration of plants is slow and therefore more likely to be disturbed (Quesada *et al.* 2006).

Secondary tropical forests provide many of the same ecosystem services as primary forests, including water quality regulation, erosion control, carbon sequestration, carbon dioxide reduction, biodiversity conservation and soil and nutrients restoration (Crk *et al*. 2009; Sánchez-Azofeifa *et al.* 2003). Lastly, secondary tropical forest foliage has the most dynamic components of TDFs (Kalácska *et al.* 2005a), which is why equal importance must be granted to them as primary tropical forests.

As of 2002, the extent of secondary forests in the tropics was estimated to be 850 million hectares (Crk *et al.* 2009). Secondary forest succession is an elemental factor for the conservation of future forest ecosystems, developing carbon budgets and increasing our understanding of ecological, biochemical and biological processes (Arroyo-Mora *et al.* 2005).

The extraordinary rate of primary forest clearing and the increasing importance of secondary forests in the tropics require increasing attention (Crk *et al.* 2009). Deforestation rates in TDFs continue to increase (Madeira *et al*. 2009) while secondary forest growth rates remain unknown (Sánchez-Azofeifa *et al.* 2005). Currently, the extent and degree of dry forest fragmentation and the long term large scale changes to tropical forest distribution remain factors less understood (Achard *et al.* 2001; Lewis *et al.* 2009).

1.3 Advancing understanding of tropical dry forests to mitigate threats

In order to begin to shed light on these aforementioned problems, an undertaking of tropical dry forest dynamics is required. Knowledge about foliage seasonality is also required for modeling biological cycles associated with vegetation (Kalácska *et al.* 2005a). Foliage provides the exchange surface between vegetation and the atmosphere by controlling the light, thermal and moisture conditions within and below the canopy (Arias *et al.* 2007; Bréda, 2003; Kalácska *et al.* 2005a). In addition, knowledge of forest composition, structure and the phenological leaf changes occurring during successional (early, intermediate, and late) growth stages (Arias *et al.* 2007; Kalácska *et al.* 2004; Madeira *et al.* 2009; Sánchez-Azofeifa *et al.*2009) is also essential.

TDFs consist of patches of successional stages that change in composition within short distances according to climate (Kalácska *et al.* 2004). In addition, they contain an understory layer (Mackenzie, 2003; Madeira *et al.* 2009) and lianas within the intermediate and late successional stages (Madeira *et al*. 2009; Sánchez-Azofeifa *et al.* 2009). Lianas are parasitic woody vines that use the forest trees for physical support to climb atop of the forest canopy, subsequently forming mat-like layers (Laurance *et al.*2001; Sánchez-Azofeifa *et al.* 2009). Lianas play an important role in tropical dry forest structure, accounting for up to 40% of leaf area and productivity (Madeira *et al.* 2009). As highly prevalent and dominant structures, lianas can critically influence tropical dry forest dynamics by suppressing seedling growth or altering light availability to the forest floor, thereby altering forest structure and regeneration (Kalácska *et al.* 2005a; Madeira *et al.* 2009).

Most research concerning tropical forests, even with regards to remote sensing, currently rests on tropical rain forests as this area receives the majority of international research funding (Arroyo-Mora *et al.* 2005; Madeira *et al.* 2009; Sánchez-Azofeifa *et al.* 2005). Currently, 14% of tropical forest research focuses on dry forests versus 86% for wet forests (Sánchez-Azofeifa *et al.* 2005). In addition, tropical forest research is limited to a few sites worldwide (Sánchez-Azofeifa *et al.* 2005). Therefore, vast amounts of research concerning TDFs is necessary to document the rate of tropical deforestation and to monitor the extent and development of secondary forests, in order to support sustainable resource development and the development of successful conservation programs (Arroyo-Mora *et al.* 2005; Madeira *et al.* 2009; Sánchez-Azofeifa *et al.* 2003, 2005).

1.4 Leaf Area Index (LAI)

The forest canopy is very dynamic and is affected by microclimatic conditions, nutrient dynamics, herbivore activities as well as many other factors (Asner *et al.* 2003). Among these factors, leaf area is the primary determinant of primary productivity, light availability and other ecosystem processes (Asner *et al.* 2003; Bréda, 2003; Eklundh *et al.* 2001). Therefore, the amount of foliage in the canopy can be used as an indicator for these factors.

Various tools can be used to determine the amount and density of canopy foliage as well as variations in canopy structure. One important tool is a ground-based biophysical parameter: Leaf Area Index (LAI). LAI is the leaf area of one side of a leaf per unit of ground area; a method for quantifying the amount of foliage in a given area (Arias *et al.* 2007; Asner *et al.* 2003; Bréda, 2003; Kalácska *et al.* 2005a,b; de Wasseige *et al.* 2003; Zhang *et al.* 2005). Because LAI is dimensionless, it can be applied over a range of scales ranging from individual trees to forest stands and even continents (Asner *et al.* 2003; Eschenbach and Kappen, 1996; Mussche *et al.* 2001; Sampson and Allen, 1995). LAI is derived from Plant Area Index (PAI), which is the combination of all plant and woody material (e.g. branches and stems) in a forest (Arias *et al.*2007; Eschenbach and Kappen, 1996; Sánchez-Azofeifa *et al.* 2009).

The LAI of a canopy is a useful tool in determining photosynthesis, light transmittance, thermal and moisture conditions (Arias *et al*. 2007; Kalácska *et al.*2005a,b; Maass *et al.* 1995; Zhang *et al*. 2005), stand primary productivity and deforestation (Bréda, 2003; Downton, 1995; de Wasseige *et al.* 2003). Moreover, the influences of vegetation on the water, energy and carbon cycles can be detected using LAI because it is the exchange area between photosynthetic vegetation and the atmosphere (Arias *et al.* 2007; Kalácska *et al.* 2005a,b). LAI can also provide information about landscape, forest restoration (Huemmrich *et al.* 2005; Kalácska *et al.* 2005a), modelling ecosystem functions (Maass *et al.* 1995), and at a broader scale, used as an indicator for determining long-term climate change (Huemmrich *et al*. 2005). Furthermore, quantifying the temporal variations of LAI is also important for understanding variation in the rates of ecosystem processes (Maass *et al.* 1995).

Lastly, LAI is closely related to forest structure (Arias *et al.* 2007; Kalácska *et al.* 2004, 2005a). More specifically, LAI positively correlates with the successional stage of the TDF as a result of micro-climatic changes that create differences in canopy openness in each successional stage (Kalácska *et al.* 2004). This correlation ultimately renders LAI a useful indicator for characterizing forests in terms of successional stage (Sánchez-Azofeifa *et al.* 2009).

Although most studies on LAI have taken place in boreal and subtropical forests, tropical hardwood species can also be monitored using LAI (Arias *et al.* 2007; Huemmrich *et al.* 2005; Kalácska *et al.* 2004, 2005a,b; Maass *et al.* 1995; Privette *et al.*

2002; Quesada *et al.* 2009; de Wasseige *et al.* 2003) however, not all methods are readily compatible with tropical dry forest measurements (de Wasseige *et al.* 2003).

1.4.1 Direct Methods

LAI can be measured *in situ* either directly or indirectly, as well as via satellites. Direct methods measure leaves directly (de Wasseige *et al.* 2003), these include destructive sampling and allometry, and indirect methods use litter traps as well as non-contact optical methods (Asner *et al.* 2003; Eklundh *et al.* 2001; Huemmrich *et al.* 2005; Kalácska *et al.* 2005b; Mussche *et al.* 2001).

1.4.1.1 Destructive Sampling

Destructive sampling consists of sampling a small amount of representative trees within a delimited area and determining the area of one side of each leaf using squared grid paper or weighing paper replicates. Alternatively, sampling can be performed by collecting leaves from a sample of trees, weighing the total foliage and determining Specific Leaf Area (SLA) (leaf area/ leaf mass) from subsamples (Arias *et al.* 2007; Asner *et al.* 2003; Bréda, 2003; Huemmrich *et al.* 2005; Jonckheere *et al.* 2004). Once the SLA is known, the LAI is calculated from the field sample by multiplying the SLA by the dry weight (Jonckheere *et al.* 2004).

Destructive sampling can measure LAI over the timeframe of collection but it cannot provide LAI values for a specific point in time during the growing season (Jonckheere *et al.* 2004). Therefore, if species can replace their leaves during the growing season, the litter trap methodology would provide overestimated LAI values (Jonckheere *et al.* 2004). These methods also tend to be too destructive for conservation areas and are more adaptable for smaller vegetation such as crops due to the labour required to obtain samples from the trees in large forest canopies (Bréda, 2003).

1.4.1.2 Allometry

Allometric methods are less destructive and use the relationship between leaf area and the physical dimensions of a tree, such as stem diameter at breast height (Asner *et al.* 2003; Bréda, 2003; Huemmrich *et al.* 2005; de Wasseige *et al.* 2003), to increase the LAI scale from tree to canopy estimates (Sampson and Allen, 1995; de Wasseige *et al.* 2003).

However, this approach may only be applied in canopies which show uniform structure between individuals and small yearly variation (Eschenbach and Kappen, 1996; Jonckheere *et al.* 2004). In addition, SLA is dependent on species, site fertility, date and year, duration of time in the traps, and weather (Bréda, 2003; Jonckheere *et al.* 2004). A notable drawback of the allometric approach is the potential susceptibility to measurement errors that can occur at each step and intensify if accumulated. For example, measurement errors can occur in leaf area/weight ratio measurements, tree diameter to leaf area relationships, and also through extrapolation from sample trees to plots and stands (Chen *et al.* 1997).

Direct measurement methods are largely time-consuming, labour intensive, cannot be applied routinely to multiple locations, and are not practical for validation of moderate resolution satellite products (Eklundh *et al.* 2001). Optical methods are thus preferred as they are considered to provide fast and accurate LAI estimates for specific time periods during the entire growing season, with a greater availability of sampling at a larger scale (Arias *et al.* 2007). Consequently, optical methods are the most widely utilized for LAI sample measurement (Jonckheere *et al.* 2004; Kalácska *et al.* 2005b; Morisette *et al.* 2006; Mussche *et al.* 2001; de Wasseige *et al.* 2003; Yang *et al.* 2006).

1.4.2 Indirect Methods

1.4.2.1 Litter traps

Indirect LAI estimations through litter traps can only be used in deciduous forests by collecting leaves in traps of a determined area below the canopy during leaf fall (Bréda, 2003). This approach measures the dry weight of the total collected leaf litter (leaf mass) and calculates LAI by multiplying the total dry mass by SLA derived from a subsample of leaves (Bréda, 2003; Bouriaud *et al.* 2003; Eschenbach and Kappen, 1996; Jonckheere *et al.*2004).

Leaf litter traps and destructive sampling can be subject to sampling errors if low sample numbers of trees are measured. As measurements are subject to the phenology in a forest, LAI values can differ due to leaf turnover depending on the time sampled. Since the plots sampled and the average amount of leaves falling in the traps are considered to be representative of the entire forest (Asner *et al.* 2003; Eklundh *et al.* 2001; Eriksson *et al.* 2005; Jonckeheere *et al.* 2004), this approach may result in a delayed estimation of LAI (Asner *et al.* 2003; Sampson and Allen, 1995).

1.4.2.2 Optical Measurements

1.4.2.2.1 Gap fraction theory

Indirect methods estimate LAI through light interception measurements (Eklundh *et al.* 2001). This optical technique is based on the relationship between gap fraction and LAI and can be applied using a number of instruments including the LAI-2000 and Hemispherical Photographs (HPs) (Bréda, 2003; Eklundh *et al.* 2001; Eriksson *et al.* 2005; Morisette *et al.* 2006; Zhang *et al.* 2005). Gap fraction is the fraction of view in a given direction from below the canopy that is not blocked by foliage (Chen *et al.* 1997; Eklundh *et al.* 2001; Sampson and Allen, 1995). Light extinction models describe the probability of interception of radiation within canopy layers, as well as the probability of sun flecks at the bottom of the canopy. Sun flecks correspond to gaps in the canopy when viewed along the direction of the direct solar beam (Jonckheere *et al.* 2004). Indirect methods estimate LAI from measurements of light above and below the canopy through a relationship based on Beers Law (Bréda, 2003; Eklundh *et al.* 2001; Jonckheere *et al.* 2004).

1.4.2.2.2 LI-COR LAI-2000

LAI can be measured with several indirect optical instruments such as hemispherical photographs or the LI-COR LAI-2000. The LAI-2000 is composed of a hemispherical lens containing five concentric rings with varying fields of view that integrates gap fraction at each zenith angle to estimate LAI (Eklundh *et al.* 2001; Erikson *et al.* 2005; Kalácska *et al.* 2005b; Sampson and Allen, 1995; de Wasseige *et al.* 2003; Zhang *et al.* 2005).

The LAI-2000 Plant Canopy Analyzer relies on the Beer-Lambert attenuation law to estimate the amount of blue diffuse radiation transmittance (400-490nm) that penetrates the canopy (Arias *et al.* 2007; Eriksson *et al.* 2005; Huemmrich *et al.* 2005; Jonckheere *et al.* 2004; Kalácska *et al.* 2005a,b; de Wasseige *et al.* 2003; Zhang *et al.* 2005). The equipment consists of a built-in optical filter that rejects incoming radiation with wavelengths above 490nm in order to minimize the radiation scattered by the canopy; thus creating a maximum contrast between the leaves and the sky (Jonckheere *et al.* 2004).

The LAI-2000 measures diffuse radiation by two components: (1) diffuse sky radiation which is radiation that reaches the sensor through canopy gaps and (2) enhanced diffuse radiation which is the simultaneous scattering of direct and diffuse radiation within the canopy (Leblanc and Chen, 2001). Under direct sunlight conditions, the leaves directly illuminated will scatter more light in the canopy that can be accounted by the "above canopy" readings, underestimating LAI values by 10-50% (Wells and Cohen, 1996). It is therefore recommended the LAI-2000 be used under diffuse light conditions to obtain optimal results. The LAI-2000 is capable of performing all computations within the console and can store all measurements and results (Jonckheere *et al.* 2004).

Several assumptions are made by the LAI-2000 for LAI calculations (de Wasseige *et al.* 2003): (i) the foliage is considered opaque and absorbs all the light it receives, (ii) the leaves are randomly distributed in a forest, (iii) the leaf is small with respect to the area of view of the detector ring; the distance from the sensor to the leaf should be four times the leaf width, (iv) the azimuth of the leaves is randomly distributed (Bréda, 2003; Eklundh *et al.* 2001; Eschenbach and Kappen, 1996; Jonckheere *et al.* 2004; Mussche *et al.* 2001; de Wasseige *et al.* 2003). With these assumptions gap fraction can be considered equivalent to transmittance (Bréda, 2003).

1.4.2.2.3 Hemispherical Photography

Like the LAI-2000, hemispherical photographs use gap-fraction methods to calculate LAI (Zhang *et al.* 2005). This is another means for measuring LAI, determining canopy architecture and solar radiation in forests (Zhang *et al.* 2005). This calculation is based on the assumptions that canopy openings allow an unblocked passage of light and that leaves block all light penetration (Rich, 1990). Using this method, canopy architecture and leaf area can be estimated (Bréda, 2003; Chen *et al.* 1997; Rich, 1990; Zhang *et al.* 2005). Hemispherical photographs provide valuable information regarding position, size, density, architecture, and distribution of canopy gaps (Bréda, 2003; Hardy *et al.* 2004; Jonckheere *et al.* 2004; Rich, 1990; Zhang *et al.* 2005).

Hemispherical canopy photography characterizes plant canopies using photographs taken looking upward towards the zenith through an extreme wide angle (180º) lens (Chen *et al.* 1997; Hardy *et al.* 2004; Jonckheere *et al.* 2004; Rich, 1990).

Hemispherical photographs have the advantage of using spatial discrimination and can acquire foliage angle distributions and gap fractions at a wide variety of zenith and azimuth angles. This is because of its 180º angle lens which produces a projection of a hemisphere on a plane (Jonckheere *et al.* 2004). This is in contrast to the LAI-2000 which has 5 concentric lenses with a field of view of 148º (Jonckheere *et al.* 2004; Rich, 1990; Zhang *et al.* 2005), allowing the hemispherical photograph to have a much larger integrating capacity than the LAI-2000 (Mussche *et al.* 2001).

1.4.2.3 Advantages of Optical Measurements

Although both the LAI-2000 and hemispherical photographs utilize diffuse light, hemispherical photographs have the added advantage of being able to provide information about canopy structure (Bréda, 2003; Zhang *et al.* 2005). Hemispherical photographs have been successfully used in a diverse range of studies to characterize canopy architecture and light penetration (Jonckheere *et al.* 2004). Using the gap size distribution theory of the TRAC instruments, digital photographs can be used to derive clumping index which characterize the spatial distribution of foliage and LAI (Zhang *et al.* 2005).The photographs can also serve as a permanent record of canopy information which can then be retrieved and further analyzed as more powerful processing software and improved models become available (Jonckheere *et al.* 2004; Rich, 1990). Specifically, these gap fraction measurements allow for comparing changes in canopy structure and heterogeneity on a temporal scale, as well as comparison to other canopies at different sites (Rich, 1990).

1.4.2.4 Disadvantages of Optical Measurements

However, in spite of these advances there are several disadvantages to this method. Firstly, optical gap-fraction methods tend to saturate above a specific LAI value; in contrast to destructive methods which are more precise and are used to calibrate indirect optical sensors (Bréda, 2003; Eriksson *et al.* 2005; Jonckheere *et al.* 2004; Kalácska *et al.* 2005b; Mussche *et al.* 2001; Yang *et al.* 2006).

Zhang *et al.* (2005) observed hemispherical photographs underestimate LAI by as much as 50% possibly due to the camera's exposure setting that influences the measurement of light transmission of the canopy. The exposure in photographs influences the grey values of unobscured pixels, which are used as the reference to determine whether pixels are completely obscured or partly obscured (Rich, 1990; Zhang *et al.* 2005). Because LAI decreases with increases in exposure, increases of gap fraction with exposure causes increased estimates of light transmittance resulting in an underestimation of LAI (Zhang *et al.* 2005).The optimum exposure for hemispherical photographs within the canopy should make the sky appear as light as possible while making the foliage as dark as possible to maximize the contrast between the sky and foliage (Zhang *et al.* 2005). Therefore, Zhang *et al.* (2005) concluded that the optimum exposure for LAI measurements is to maintain overexposure by two aperture stops relative to the sky reference.

Secondly, the optical gap- fraction method of the LAI-2000 cannot differentiate between light intercepted by foliage or other plant elements such as the woody components of stems, trunks and branches (Asner *et al.* 2003; Bréda, 2003; Eriksson *et al.*2005; Jonckheere *et al.* 2004; Kalácska *et al.* 2005b; de Wasseige *et al.* 2003; Yang *et al.* 2006). This property is characteristic of all gap-fraction based approaches (Jonckheere *et al.* 2004), including HPs where the problem of not being able to discriminate photosynthetic material from that of woody material such as stems and branches is also encountered (Mussche *et al.* 2001) Therefore, much like the LAI-2000; it is also said that HPs calculate PAI and not LAI directly (Mussche *et al.* 2001).

Thirdly, another major problem that has been acknowledged within the literature is the selection of optimal brightness threshold of HP's upon which the software determines which pixels are dark (sun obscured) and which pixels are white (light penetrated); this adds a level of subjectivity to the analysis and overrepresent areas that have large openings and underrepresent areas that have small canopy openings (Jonckheere *et al.* 2004; Rich, 1990).

Lastly, gap fraction methods have been found to underestimate LAI in discontinuous and heterogeneous canopies. The underestimation is largely due to the assumption of randomly distributed leaves which is applied by most instruments to predict LAI with gap fraction measurements (Jonckheere *et al.* 2004). In reality, vertical and horizontal distributions are not homogenous within a forest due to differences in light accessibility (Asner *et al.* 2003; Bréda, 2003; Eklundh *et al.* 2001; Eriksson *et al.* 2005; Eschenbach and Kappen, 1996; Jonckheere *et al.* 2004; Kalácska *et al.* 2005b; de Wasseige *et al.* 2003). Therefore, LAI-2000 values also vary according to successional stage, with estimates at earlier stages having weaker relationships than those at later stages, due to species composition, percent in canopy cover and heterogeneity of canopy cover (Kalácska *et al.* 2005b).

Canopy architecture can be separated into two essential attributes: leaf angle and leaf spatial distribution (Chen *et al.* 1997). Because both the LAI-2000 and HPs obtain gap fraction information under a wide range of angles they do not require previous knowledge of leaf angle distribution (Chen *et al.*1997). However, because gap fraction models assume that leaves are randomly distributed, incorrect LAI estimates are usually obtained (Chen *et al.* 1997). Foliage clumping also results in biased LAI estimates (Eschenbach and Kappen, 1996; Yang *et al.* 2006b) and reduces the accuracy of LAI measurements in high LAI stands such as broadleaf forests (Yang *et al.* 2006b). In particular, foliage clumping seems to be the main factor causing errors in LAI estimation on the part of the LAI-2000 and HPs (Jonckheere *et al.* 2004).

For a clumped, non-homogeneous canopy structure, the underestimation can be even greater due to very local and specific penetration points of radiation through the canopy (Mussche *et al.* 2001). Lastly, weather conditions such as sunny skies or even fast moving clouds can further distort LAI estimates (Mussche *et al.* 2001).

Kalácska *et al.* (2005b) researched the relationship between direct methods and indirect optical measurement methods in TDFs. Once woody area values were removed from the LAI-2000 readings, they were closely correlated to LAI values measured in leaf litter traps. The strongest relationships were observed in the late stage which is characterized by having a more uniform and closed canopy.

Few studies have used the LAI-2000 instrument to assess LAI in tropical dry forest environments (de Wasseige *et al.* 2003). To elucidate the characteristics of this biome, indirect optical measurement methods were chosen for the present study as these methods allowed for rapid measurements over a period of 3 years and captured phenological changes of the plot site throughout the years.

1.4.3 Determining LAI using Remote Sensing Satellites

In the past, sampling methods used to measure the biophysical characterization of foliage were primarily ground-based (de Wasseige *et al.* 2003). Nonetheless, remotely sensed LAI data acquisition through satellite measurements is now being considered as a more economical and logistically applicable approach than *in situ* methods (Kalácska *et al.* 2005a). Remote sensing allows monitoring of foliage over large areas at a more frequent temporal scale, leading to a fuller understanding of leaf biomass and forest structure (de Wasseige *et al.* 2003).

Currently LAI is the driving factor of most reflectance information received through remote sensing (Eklundh *et al.* 2001; de Wasseige *et al.* 2003). Remotely sensed data can help in this respect by providing information about the state of ecosystems, thereby helping policy makers create and protect corridors, conservation areas, and pursue issues such as climate change and forest fragmentation (Kalácska *et al*. 2005; Sánchez-Azofeifa *et al.* 2003).

Remote sensing research is very limited particularly in secondary tropical forests. This lack of research is in part due to the complexity and diversity of such systems at both the tree and landscape scale as well as the lack of infrastructure in these areas available for research (Arroyo-Mora *et al.* 2003; Sánchez-Azofeifa *et al.* 2003). Most research on LAI has been carried out on conifer stands and broadleaf forests in boreal (Leblanc *et al.* 2005) and temperate regions (Mussche *et al.* 2001*;* Soudani *et al.* 2006). As of 2003, only 8% of the entire global database was based on tropical regions (Kalácska *et al*. 2005b). Little research on LAI has been conducted for TDFs (Sánchez-Azofeifa *et al.* 2009) while temporal LAI studies are even more scarce (Kalácska *et al*. 2005b).

1.4.3.1 Types of Remote Sensing Satellites

Remote Sensing Satellites can be divided into 2 types: multispectral and hyperspectral. Multispectral satellites measure the intensity of light reflected from the earth’s surface along broad spectral bands, for example Landsat Thematic Mapper (TM) (Sánchez-Azofeifa *et al.* 2003). Hyperspectral satellites measure spectral reflectance along narrow contiguous bands, usually providing reflectance for 200 bands or more (Sánchez-Azofeifa *et al.* 2003).

1.4.3.2 Satellite Resolution

There are several types of remote sensing satellites with varying resolutions. Firstly there are coarse resolution satellites such as the Moderate Resolution Imaging Spectroradiometer (MODIS), as well as medium resolution satellites, among them SPOT HRV, ASTER and Landsat TM with resolution capability of 30-15m (Sánchez-Azofeifa *et al*. 2003). High resolution satellites are categorized as having spatial resolutions lower than 5m (Sánchez-Azofeifa *et al.* 2003). Satellites such as IKONOS-2 and Quickbird provide high-resolution satellite imagery. Remote sensing observations acquired with moderate resolution sensors allow monitoring of seasonal and interannual variability of LAI over regional or global domains (Garrigues *et al.* 2008).

Coarse spatial resolution satellites can be utilized to obtain information on the extent and status of TDFs. In November 1999, NASA launched Terra an Earth Observation Systems (EOS) platform (Privette *et al.* 2002). Terra has five sensors including MODIS. MODIS has a wide field of view of 2330km, with 36 spectral bands at 250m, 500m and1km resolutions (Privette *et al.* 2002). The MODIS Land Discipline Team (MODLAND) has been generating a wide variety of products at different temporal and spatial resolutions, including LAI (Privette *et al.* 2002).

1.4.3.3 MODIS LAI product

The MOD15A2 is the LAI FPAR (Leaf Area Index and Fraction of Photosynthetically Active Radiation) product which has been recording LAI/FPAR measurements since June, 2000 until present (Morisette *et al.* 2006; Aragão *et al.* 2005). Measurements are produced on an 8-day compositing period at a 1-km spatial resolution, where the selected LAI value for the compositing period recorded on the day with the highest Fraction of Photosynthetically Active Radiation (FPAR) (Aragão *et al.* 2005; Morisette *et al.* 2006; Privette *et al.* 2002).

1.4.3.4 MODIS-LAI algorithm

The MODIS algorithm is based on a three-dimensional radiative transfer model and modified to allow inversion using look-up tables (LUT) (Aragão *et al.* 2005; Garrigues *et al.* 2008; Privette *et al.* 2002). The MODIS red and near infrared (NIR) atmospherically corrected reflectance values and the corresponding illumination-view geometry are used as inputs for the LUTs (Garrigues *et al.* 2008). The algorithm output is the mean LAI computed over the set of acceptable LUT elements where the simulated and measured reflectance values are within specified uncertainty levels (Garrigues *et al.* 2008). The MOD15 algorithm is based on the daily surface reflectance product (MOD09). The MOD09 product correction scheme uses the MOD05 for water vapour, the MOD04 product for aerosols, the MOD07 product for ozone and MODIS band 26 for detection of cirrus clouds (Fensholt *et al.* 2004).

The algorithm works by using atmospherically corrected bidirectional reflectance (BDRF) values and their corresponding sun-angles for up to seven spectral bands (Fensholt *et al.* 2004; Privette *et al.* 2002). The MOD09 product comprises all MODIS reflectance for each band as it would be measured on the ground without atmospheric scattering or absorption (Fensholt *et al.* 2004). Along with these values, another input is used; the MODIS land cover product (MOD12), which incorporates a 1km land cover map that is divided into the world’s six major biomes (Fensholt *et al.* 2004; Privette *et al.* 2002). Each biome is assigned a surface characteristic regarding canopy architecture and the optical properties of the vegetation derived from a radiative transfer model (Fensholt *et al.* 2004). LAI is first produced daily and the LAI value generated from the main algorithm corresponding to the maximum FPAR is subsequently selected over an 8-day period (Garrigues *et al.* 2008).

The LUTs are then generated for each biome by running the model for many combinations of LAI and land cover (Privette *et al.* 2002). During this stage, the algorithm compares the observed reflectance values for a particular biome to the estimated values in the LUT using constants on soil properties, canopy structure, leaf angle distribution, wood and litter optical properties (Fensholt *et al.* 2004; Privette *et al.* 2002). The LAI algorithm is restricted to the infrared (IR) and NIR bands as atmospheric effects are much stronger at blue bands than red bands, which reduce the amount of uncertainties when solving for LAI using BRDF (Fensholt *et al.* 2004). The MODIS algorithm accounts for vegetation clumping at the canopy and at the shoot scale through the three-dimensional radiative transfer algorithms (Garrigues *et al.* 2008).

1.4.3.5 Uncertainties in the MODIS-LAI algorithm

Uncertainties can come about when vegetation gradients are categorized into 6 biome classes. This can leave out very important land classes (Fensholt *et al.* 2004) such as TDFs that are categorized as savannahs and shrubs according to the MODIS classification map. In addition, the upper layers of dense canopies completely obscure the reflectance from the lower leaves and in turn render the measurement process insensitive to reflectance from the understory. Such a phenomenon is known as saturation (Fensholt *et al.* 2004; Myneni *et al.* 2002). Saturation effects in the algorithm make the probability of a solution to be equal among many values, making the output far less accurate (Fensholt *et al.* 2004; Myneni *et al.*2002).

Uncertainties may also occur due to variations in sun-sensor geometry, canopy structure, and uncertainties within the atmospheric correction effects (Fensholt *et al.* 2004). Bidirectional reflectance effects can also affect remote sensing data (Sánchez-Azofeifa *et al.* 2003). These effects are mostly due to soil reflectance, reflectance of thick vegetation, and saturation (Sánchez-Azofeifa *et al.* 2003). Vermote (2000) estimates MODIS uncertainty in the red band to be 10-33%, and 3-6% at the NIR band, whereas Huang *et al.* (2003) estimates the average uncertainties in the MODIS red and NIR reflectance values to range from 10-15%.

When the uncertainty of the estimated reflectance values are less than the uncertainty of the observed reflectance, the LAI products are considered as acceptable solutions (Cohen *et al.* 2006; Fensholt *et al.* 2004; Privette *et al.* 2002). The mean value of LAI averaged over all the acceptable solutions is given as the final output (Fensholt *et* *al.* 2004). However, if the estimated reflectance uncertainty is greater than the observed reflectance, the solutions are deemed unacceptable and a back-up algorithm is employed based on the LAI-NDVI (Normalized Difference Vegetation Index) relationship. However, this relationship is site-specific and is only valid when calibrated over a specific soil type (Fensholt *et al.* 2004). Therefore, the LAI-NDVI relationship is calibrated over the same simulations used to build the LUTs of the main algorithm (Aragão *et al.* 2005; Cohen *et al.* 2006; Fensholt *et al.* 2004; Garrigues *et al.* 2008; Privette *et al.* 2002). The majority of the back-up algorithm retrievals are performed under the presence of snow and clouds (Garrigues *et al.* 2008). This is disadvantageous to remote sensing research in the tropics since cloud cover is persistent in this region due to high humidity (Achard *et al.* 2001; Arroyo-Mora *et al.* 2005; Sánchez-Azofeifa *et al.* 2003).

1.4.3.6 Disadvantages of satellite-based information for tropical dry forests

There are several disadvantages regarding satellite-derived information of secondary tropical forests. Because of seasonal changes, tropical dry forests undergo periodic phenological transformations that render them leafless for several months of the year (Sánchez-Azofeifa *et al.* 2003; Kalácska *et al.* 2005b). This causes the light reflectance signal to increase or decrease respectively with the presence or absence of leaves (Sánchez-Azofeifa *et al.* 2003). Such variations can in turn lead to erroneous classification of biomes. As an example, tropical dry forest ecosystems have been previously classified as pasture lands because in the dry season leafless tropical forests have the same reflectance signature as pastures and savannahs (Sánchez-Azofeifa *et al.* 2003). As a result of seasonality, it is also difficult to define secondary forest succession which leads to misclassified, misrepresented and underestimated extents of secondary tropical dry forests (Arroyo-Mora *et al.* 2005). Thus understanding phenological events is crucial for the study of remote sensing in tropical dry forests.

Chapter 1: Evaluation of MODIS-LAI products in the tropical dry forest of Mata Seca, Minas Gerais, Brazil

1. INTRODUCTION

1.1 Tropical Dry Forests

Tropical forests are most often equated with tropical rainforests. However, the term encompasses many types of forest in the tropics. Tropical forests are composed of open and closed forests. Closed tropical forests consist of two main types: wet tropical forests and seasonally dry tropical forests (Mackenzie, 2003). Tropical Dry Forests (TDFs) are characterized by having a pronounced seasonality, divided into a wet season and dry season. The wet season brings heavy rainfall, whereas the dry season, is characterized as having 4-6 months of little or no precipitation (Kalácska *et al.* 2005b; Mackenzie, 2003; Miles *et al.* 2006; Quesada *et al.* 2009). According to the FAO (Food and Agriculture Organization; United Nations) tropical forests comprise 47% of global forest cover and tropical dry forests comprise 42% of tropical forests (Kalácska *et al*. 2004, 2005b; Quesada *et al.* 2009).

Moreover, TDFs can be further subdivided into primary and secondary forests (Corlett, 1995). Secondary forests can be defined as forests that have regrown as a result of a major disturbance with differences (Corlett, 1995; Chazdon *et al.* 2009). The extent of tropical secondary forests is estimated to be 850 million hectares (Crk *et al.* 2009; ITTO, 2002). Tropical secondary forests contribute to many of the same ecosystem processes as primary forests (Crk *et al.* 2009) including water quality regulation and flow, erosion control, carbon sequestration, restoration of nutrients, biodiversity conservation and reduction of area fragmentation (Crk *et al.* 2009, Sánchez-Azofeifa *et al.* 2003).

However, TDF health is being threatened by many factors such as fire (Miles *et al.* 2006), climate change, (Studer *et al.* 2007; Miles *et al.* 2006) as well as agricultural development (Kalácska *et al.* 2005b, Quesada *et al.* 2009) which is why the current monitoring of LAI in TDFs is becoming increasingly important. The increasing importance of secondary forests in performing these services (Crk *et al.* 2009*)* and the ever-increasing rates of primary forest clearing in the tropics is fostering a need to evaluate and understand the biophysical parameters associated with these services.

1.2 Conservation value of Secondary Forests

1.2.1 Role of secondary forests in mitigating primary forest loss

Recently, a heated debate has emerged between prominent researchers in the field on the validity and conservation value of tropical forests (Brook and Bradshaw, 2006; Harrison, 2001; Laurance, 2006a; Wright 2006 a,b). Wright (2006a,b) contends that for the past two decades secondary forests have reclaimed 1 hectare of land for every 6-7 hectares that have been deforested, and landscapes are being transformed into forested islands amidst agricultural fields. Currently, there are more secondary forests than old growth forests (Dent, 2010) and this is also the case for the majority of tropical countries today (Corlett, 1995). Secondary forests have the capability to develop into forests of similar structure and species composition as old growth forests provided they are close to old growth sites and are not continually disturbed (Wright, 2006a). Therefore, Wright and Muller-Landau (2006b) postulate that secondary forest recovery will buffer the rate of forest cover loss as old growth forest cover decreases due to conversion of landcover to agricultural land. According to Corlett (1995), secondary forests will fulfill the needs that once were provided by primary forests. Because of the vast areas covered by secondary forests, they are becoming increasingly important in curtailing habitat fragmentation, promoting biodiversity conservation and providing ecosystem services (Wright, 2006a,b).

1.2.1.1 Expansion of Habitats

Secondary forests provide sheltered areas, habitats and resources for animal species (Barlow *et al.* 2007; Dirzo *et al.* 2011). In addition, secondary forests help to provide suitable habitats for old growth forests species that are confined to small growth areas (Chazdon *et al.* 2009; Gardner, 2007). Currently, there are high proportions of tropical forest species residing in secondary forests, which buffer against habitat fragmentation (Harrison, 2011), providing more habitat space for old growth forest species and reducing the likelihood of extinction. Wright and Muller-Landau (2006b) propose that secondary forest regrowth will decrease species extinctions caused by reductions of old growth forest habitat, serving as a safety net for biodiversity.

1.2.1.2 Development of Biodiversity

Secondary forests play a vital role in the conservation of biodiversity and should therefore be given considerable attention (Dent, 2010) as they are more suitable for conservation than other land-use types (Gardner, 2007). Secondary forests are often composed of a high diversity of plant species and help to increase biodiversity (Barlow *et al.* 2007; Dirzo *et al.* 2011).The most fundamental approach for enhancing biodiversity in agricultural landscapes is to increase the amount, diversity and connectivity of tree cover (Dirzo *et al.* 2011). This can also be said for tropical dry forests which also show a high capacity for recovering vegetation structure and biodiversity through succession after the land has been altered through agricultural use (Dirzo *et al.* 2011). Small forest stands in agricultural areas enhance biodiversity (Wright, 2006a) and as secondary forests develop into older stands, species richness and species recovery increase (Brook and Bradshaw, 2006; Gardner, 2007; Wright, 2006a). Although not all secondary forests are in the late stage of growth, these areas should nonetheless be conserved as even a mixture of different aged secondary forest patches can maximize biodiversity conservation by providing heterogeneous habitats (Barlow *et al*. 2007; Chazdon *et al*. 2009).

1.2.1.3 Production of Ecosystem Services

Ecosystem services contribute considerably to human well-being. Therefore, it is imperative that the ability for ecosystems to provide these services is maintained for the long-term future (Dirzo *et al.* 2011). Apart from secondary forests providing sources for wildlife, forest products (Barlow *et al.* 2007; Chazdon *et al.* 2009) and ecosystem services (Corlett, 1995), secondary tropical forests also capture CO_2 at a rate more efficient than primary forests due to their rapid biomass accumulation (Barlow *et al.* 2007; Corlett, 1995). Studies of forests in temperate zones have noted that secondary forests are able to restore biotic hydrology regulation and biogeochemistry of an area very rapidly and it is safe to assume this is also the case for tropical secondary forests (Corlett, 1995).

Ultimately, these conclusions raise questions of whether secondary tropical forests have the same conservation value as primary tropical forests. Because of these secondary forest characteristics, considerable attention should be given to secondary forests (Dent, 2010) as they are more suitable for conservation than other land-use types (Gardner, 2007).

1.2.2 Problems concerning secondary forests as buffers for primary forest loss

1.2.2.1 Conservation of Biodiversity

Although some scientists believe that secondary forests are as equally valuable for conservation as primary forests, there are others who oppose this “too optimistic” view regarding the importance of secondary tropical forests (Brook and Bradshaw, 2006; Laurance, 2006). From their viewpoint, the general understanding of secondary forests is still too weak to rely on secondary forests for biodiversity conservation (Gardner, 2007). Brook and Bradshaw (2006) also argue that secondary forests are less developed than old growth forests with reduced ecosystem services and thus harbour lower biodiversity than old growth forests. Secondary forests also tend to support fewer tree species with different species compositions than old growth forests (Corlett, 1995). The lower plant diversity in secondary forests could be attributed to the inability of primary forest species to disperse to an alternate site. For wind dispersed species, this decrease in diversity could be due to the large distances between sites, and for animal-dispersed species animal loss due to hunting or the unwillingness of animals to enter into open areas could be attributed to this lack of diversity (Corlett, 1995). Therefore, secondary forests always have less species diversity than primary forest which cannot always be compensated by increasing their conservation areas (Corlett, 1995).

1.2.2.2 Difficulties with endemic and specialist species

Moreover, secondary forests have more open vegetation and dispersed canopies with a sparse understory that only support generalist species (Brook and Bradshaw, 2006). Species that are not consistently present in secondary forests are also more prone to extinction (Brook and Bradshaw, 2006; Dent, 2010; Laurance, 2006; Wright and Muller-Landau, 2006b) because species likely to be absent are those with specialized dietary requirements or sensitive to a particular type of forest (Corlett, 1995). Therefore old growth forest species will inevitably be lost (Gardner, 2007). Furthermore, secondary forests are likely to be very heterogeneous, few have nearby old growth forests and those that do are poorly connected, thereby making species conservation difficult (Gardner, 2007).

Generally, it has been agreed that there is no reliable data as to whether secondary forests can be considered a refuge for endangered species and determining the proportion of old growth species that can persist in secondary forests remains to be determined (Dent, 2010). It is also agreed that there is a need to evaluate the degree to which regeneration of habitats is truly able to sustain old growth habitats and thus play a key role in biodiversity conservation and therefore in secondary forest conservation (Laurance, 2006).

Notwithstanding, the value of secondary old growth forests is expected to increase as species from old growth areas move in (Chazdon *et al.* 2009). Although endemic or specialist old growth forest species may not be present, old secondary forests contain 59% of species found in old growth forests (Chazdon *et al.* 2009) suggesting that in time, an influx of old growth species into older secondary successional forests occurs, increasing the importance of their conservation value (Chazdon *et al.* 2009).

The conservation value of secondary forests will depend on the proportion of species whose habitat is restricted to old-growth forests (Wright, 2005). Nevertheless, determining the conservation value of a degraded habitat is a complex issue (Barlow *et al.* 2007). Therefore, disagreements arise about whether secondary forest conservation should take precedence over primary forests. In general, secondary forests cannot substitute for primary forests in biological conservation (Corlett, 1995). However, as previously stated, secondary forests can support many of the plant and animal species in areas where all of the primary forest has disappeared. By providing a link between islands of remaining primary forest, secondary forests can supply the needs of a higher proportion of species than either would be able to do on its own (Corlett, 1995).

Lastly, in order to comprehensively understand all the ecosystem services associated with tropical dry forests and to help provide a quantitative answer as to how tropical secondary forest behave, what services they provide, their conservation value amidst the decreasing status of primary forests, further investigation is required using all available variables that are associated with these services.

1.3 Leaf Area Index

1.3.1 Definition and applicability

One such useful biophysical variable associated with ecosystem services is Leaf Area Index (LAI). It is defined as the measure of half the surface leaf area per square meter of ground (m^2/m^2) (Bréda, 2003; Fensholt *et al.* 2004; Morisette *et al*. 2006). LAI can be used to indirectly monitor leaf gas exchange and estimate forest carbon assimilation, in addition to being an indicator for forest water content and overall forest health (Bréda, 2003; Morisette *et al.* 2006). Because LAI is a driver of many biogeochemical cycles, and a contributor to the biophysical properties of the forest (Bréda, 2003); any changes in LAI within the forest can be used indirectly to determine and monitor forest health as a measure of stand productivity (Bréda, 2003; Kalácska *et al*. 2005a).

There have been numerous studies dedicated to determining biophysical changes using LAI for many forest types including coniferous, (Wang *et al.* 2004; Cohen *et al*. 2003; Sampson and Allen, 1995; Eklundh *et al.* 2001), temperate-deciduous (Ahl *et al.* 2006; Bouriaud *et al.* 2003; Dufrêne and Bréda, 1995; Soudani *et al.* 2006), as well as tropical forests (de Wasseige *et al.* 2003; Doughtry *et al.* 2008; Kalácska *et al.* 2005a,b). Focus on LAI studies in tropical environments have mainly been conducted on rainforests while overlooking deciduous dry forests (Arroyo-Mora *et al.* 2005; Sánchez-Azofeifa *et al.* 2005).

There are various ways to measure LAI, ranging from direct ground measurements such as leaf litter traps (Bréda, 2003; Bouriaud *et al.* 2003; Chen *et al.*1997; Eriksson *et al.* 2005; Eschenbach and Kappen, 1996; Kalácska *et al.* 2005b; Mussche *et al.* 2001; Sampson and Allen, 1995); to indirect *in situ* methods such as the LAI-2000 (Arias *et al.* 2007; Bréda, 2003; Chen *et al.*1997; Eklundh *et al.* 2001; Eschenbach and Kappen, 1996; Fensholt *et al.* 2004; Kalácska *et al.* 2005b; Mussche *et al.* 2001; Sampson and Allen, 1995; Yang *et al.* 2006b) and Hemispherical Photography (HP) (Bréda, 2003; Chen *et al.*1997; Hardy *et al.* 2004; Jonckheere *et al.* 2004; Mussche *et al.* 2001; Rich *et al.* 1990; Zhang *et al.* 2005), or through satellite imagery such as Moderate Resolution Imaging Spectroradiometer (MODIS) (Fensholt *et al.* 2004; Garrigues *et al.* 2008; Huemmrich *et al.* 2005; Morisette *et al.* 2006; Privette *et al.* 2002; Yang *et al.* 2006b). Indirect methods are preferred over direct methods as they cover larger areas and are less intrusive and time-consuming (Morisette *et al.* 2006). However, indirect LAI measuring devices such as that of the MODIS, can become incompatible with other remote sensing LAI measurements when used for comparison between datasets since their accuracy is scale-dependent (Morisette *et al.* 2006). Therefore, since MODIS-LAI products have the potential to facilitate data collection (Morisette *et al.* 2006), systematic validation of their accuracy against ground data becomes of significant importance (Morisette *et al.* 2006).

1.4 Objectives

The major goal of this study is to explore how MODIS-LAI satellite products perform as a function of successional stage and to determine how these products supplement ground-based LAI information at a 1km scale. LAI products collected from 2008-2010 at a TDF in Minas Gerais, Brazil are compared both at the satellite and ground base level. To achieve this, the minor goals of this study were to:

1. Assess MODIS-LAI product agreement to *in situ* LAI values as a function of successional stage for the growing season as well as to assess agreement between *in situ* WAI and MODIS-LAI dry-season values using regression analysis to determine the correlation between values using p-value and RMSE as indicators of significance

2. Assess agreement of phenological measurements between MODIS-LAI and *in situ* LAI through a TIMESAT extraction of seasonal parameters: Start of Season, End of Season, Length of Season

2. METHODS

2.1 Study Area

This study used long term TDF research forest plots forming part of the TROPI-DRY networks (Nassar *et al.* 2008). All plots in the study were located at the Parque Estadual da Mata Seca (PEMS), a conservation area managed by Instituto Estadual de Florestas in Minas Gerais, Brazil (Fig. 1**)** (Madeira *et al.* 2009; Sánchez-Azofeifa *et al.* 2009). PEMS constitutes an area of 10281ha located between 14º48’36”- 14º56’59”S and 43º55’12”- 44º04’12”W. This area is defined by a tropical semi-arid climate with an average temperature of 24ºC, an average annual precipitation of 818± 242mm (Madeira *et al.* 2009) and a severe dry season which is present during the southern hemisphere’s winter (May-October) (Madeira *et al*. 2009; Sánchez-Azofeifa *et al.* 2009). The vegetation in PEMS is characterized as tropical dry forest stands with flat and nutrient rich soils. Vegetation growth consists of deciduous trees that lose leaves during the dry season (Madeira *et al.* 2009; Sánchez-Azofeifa *et al.* 2009). The landscape in PEMS resembles a mosaic of dry forest areas where approximately 1,525ha is covered with abandoned pasture fields and forested areas in the early regeneration stage, while the remaining areas consist of dry forest fragments in secondary and primary stages (Madeira *et al.* 2009).

2.2 Field sample design and data collection

The PMES study area is divided into 9 plots of 20m x 50m (0.1ha each) which were set up in early, intermediate and late successional stages, using 3 plots per stage (Madeira *et al*. 2009). The early successional stage is composed of sparse patches of woody vegetation, shrubs and grasses. The intermediate stage is composed of a canopy of deciduous trees, and a dense understory containing young trees and lianas. The late stage is composed of a canopy of tall deciduous trees and a sparse understory with low light penetration (Madeira *et al*. 2009; Kalácska *et al.*2005b; Sánchez-Azofeifa *et al.* 2009).

Three 20m x 50m plots within each successional stage (early, intermediate, late) were measured for LAI and Woody Area Index (WAI). As relatively high sampling rates are recommended for areas like South America (Garrigues *et al.* 2008), measurements were repeated in the same locations over a 3-year period from January 2008 to December 2010 on a bi-weekly basis. Such a frequency is particularly useful to measure seasonal and inter-annual changes in LAI and WAI. Measurements were made using an offset grid sampling scheme providing maximum area coverage without overlapping, similar to the scheme designed by Kalácska *et al.* (2005b) (Fig. 2).

One hundred plot measurements were made in the early successional stage encompassing a triangular area of 5x6m and covering 83% of the total plot area. Thirty six measurements were made in the intermediate stage encompassing an 8x10m triangular area and covering 80% of the plot area. Twelve measurements were made in the late successional stage encompassing a triangular area of 15x18m and covering 90% of the total plot area (Nassar *et al.* 2008). Since the total zenith field of view for the LAI-2000 is 148º, the maximum horizontal distance available for measurement is three times the height of the canopy (de Wasseige *et al.* 2003). Therefore, taller canopies provide more plot coverage requiring fewer measurements. Measurements in each plot were then averaged to obtain a single LAI value, which was then compared with the corresponding MODIS pixel LAI value.

2.2.1 In situ measurements

2.2.1.1 Plant Area Index

The LAI-2000 measures all light intercepting the canopy from all materials including non-photosynthetic material such as the woody parts of the forest (Arias *et al*. 2007; Bréda, 2003; de Wasseige *et al.* 2003; Kalácska *et al.* 2005a; Leblanc and Chen, 2001). These measurements are most accurately defined as the Plant Area Index (PAI) (Arias *et al.* 2007; de Wasseige *et al.* 2003; Eschenbach and Kappen, 1996; Kalácska *et al.* 2005b). PAI values were measured using the LICOR LAI-2000 Plant Canopy Analyzer in conjunction with the use of the Beer-Lambert attenuation law to estimate the amount of blue radiation (400-490nm) that penetrates the canopy (Arias *et al.* 2007; Eriksson *et al.* 2005; Huemmrich *et al.* 2005; Jonckheere *et al.* 2004; Kalácska *et al.* 2005a,b; de Wasseige *et al.* 2003; Zhang *et al.* 2005).

The LAI-2000 consists of a sensor bar, a fisheye lens and a data logger which computes light differences above and below canopy (Jonckheere *et al.* 2004) using 5 concentric rings, the device simultaneously captures gap fraction at five different zenith angles (0º-74º) while integrating all values to determine PAI (Eklundh *et al.* 2001; de Wasseige *et al.* 2003; Sampson and Allen, 1995). Above-canopy measurements were taken before and after measuring a plot site and a 45º view cap was used to remove the operator from the field of view. The PAI values were then processed using the FV2000 software (LAI-2000 File Viewer v.1.11; LI-COR, Lincoln, NE), which accompanies the LAI-2000.

The FV2000 software calculates LAI values as follows (LI-COR Inc, 1992): the LAI-2000 readings consist of a minimum of ten numbers, five of which correspond to the five sensor rings measured above the canopy, while the remaining five correspond to the sensor readings below the canopy (LI-COR Inc, 1992). The corresponding above and below measurement pairs for each ring are divided to obtain canopy transmittance (LI-COR Inc, 1992). By obtaining the transmittance at all five zenith angles, the LAI-2000 calculates LAI (LI-COR Inc, 1992).

To further increase measurement accuracy, the LAI-2000 minimizes radiation scattered by the foliage by means of a filter (Jonckheere *et al.* 2004). This filter removes all light over 490nm, that is, scattered light (Jonckheere *et al.* 2004). However, under sunny conditions, the direct beam of light shines on the foliage causing scattered radiation to increase significantly (www.licor.com). In turn, scattered light increases below-the-canopy readings thereby reducing gap fraction differences which result in underestimation of PAI (Mussche *et al.* 2001; www.licor.com). Consequently, the LAI-2000 was only used under diffuse or overcast sky conditions to minimize the potential for PAI underestimation (Bréda, 2003; de Wasseige *et al*. 2003).

2.2.1.2 Obtaining WAI through hemispherical photography and GLA analysis

Hemispherical Photographs (HP) were collected during the dry season to determine the influence of woody elements on the Plant Area Index. WAI is the woody material contribution to PAI (Kalácska *et al.* 2005a; Sánchez-Azofeifa *et al.* 2009). WAI was obtained using a fisheye lens to capture solar obstruction and penetration in the canopy (Kalácska *et al.* 2005a; Zhang *et al.* 2005). A 180º fisheye lens was placed on a Pentax *ist DS camera, levelled with a tripod and oriented north. This decreases the amount of error stemming from orientation and position (Rich, 1990). HPs were also taken under diffuse or overcast skies to reduce underestimation of LAI measurements (Chen *et al.* 1997; Leblanc *et al*. 2005). In this study HPs were taken on the same dates and during the same time frames as the LAI-2000 measurements. Using the Gap Light

Analyzer (GLA) v. 2.0 software (SFU-IES, 1999), the number of sun-obstructed (black) and penetrated (white) pixels were used to determine LAI (Hardy *et al.* 2004, Rich, 1990). By categorizing pixels as black or white relative to a specific threshold value, each pixel in the photograph is determined to be either woody material or open sky. Lastly, the processing of HPs of the dry season (characterized by an absence of leaves), HPs allows calculation of the WAI for a particular year (Eriksson *et al.* 2005; Kalácska *et al.* 2005a).

2.2.1.3 Calculating Leaf Area Index (LAI)

To improve the accuracy of LAI measurements, the woody components must be removed from PAI values. Therefore, the WAI values obtained by the HPs are factored out from the PAI obtained by the LAI-2000, giving the effective leaf area index (LAI_e) or *in situ* LAI (Chen *et al.* 1997; Kalácska *et al.* 2005b; Sánchez-Azofeifa *et al.* 2009). LAI was calculated through the following equation (Eq. 1):

$$LAI = PAI\ (1-\alpha) = \frac{LAI_e(1-\alpha)}{\Omega}$$

Where α is the ratio of WAI to PAI (Chen *et al.* 1997; Kalácska *et al.* 2005b) and the term Ω describes the foliage spatial distribution referred to as the clumping index (Chen *et al.* 1997). This study will assume leaf clumping to be random ($\Omega = 1$) (Chen *et al.* 1997) after the study of Kalácska *et al.* (2005b) that concluded that the high number of tree species with varying branch geometries, along with lack of species dominance allowed leaf clumping to be assumed as random. This method calculates the *in situ* LAI values which can be compared to the MODIS-LAI products.

2.2.2 Comparison of reference in situ LAI measurements to satellite data

Regression analyses were used to model the relationship between *in situ* LAI values and MODIS-LAI at each plot site. The *in situ* LAI values were used as the reference measurements for comparing the accuracy of MODIS-LAI products. The R^2 value was used to assess the closeness of the relationship and the RMSE was used to estimate the deviation from the regression line between the two LAI estimates (Zhang *et al.* 2005).

2.2.2.1 MODIS LAI product retrieval

MODIS Collection 5 LAI products were obtained from MODIS Global Subsets (Oak Ridge National Laboratory Distributed Active Archive Center). The MODIS "Leaf Area Index (LAI) and Fraction of Photosynthetically Active Radiation (FPAR) composite" products (MOD15A2) were chosen as 1km by 1km products for each MODIS pixel. Approximately 160 images were acquired from January 2008 to December 2010 using the dates most approximate to those of the *in situ* measurements taken at each successional stage. The NASA Land Processes Distributed Active Archive Centre (http://LPDAAC.usgs.gov) provided the MODIS subset images that were then sorted according to the algorithm use.

2.2.2.2 LAI algorithm

The MODIS-LAI algorithm is based on the radiative transfer model which uses look-up tables (LUTs) to calculate LAI (Aragão *et al.* 2005; Garrigues *et al.* 2008; Privette *et al.* 2002). Red and NIR reflectances and their corresponding view geometries are used as the inputs for the lookup tables (Garrigues *et al.* 2008). If the estimated reflectance uncertainty is less than the observed reflectance uncertainty, they are considered as acceptable solutions (Cohen *et al.* 2006; Fensholt *et al.* 2004; Privette *et al.* 2002). The algorithm output is the average LAI of all acceptable LUT solutions

(Garrigues *et al* 2008). However, when the uncertainty of the LUT estimated outputs are higher than the observed reflectances, a back-up algorithm is used based on the NDVI-LAI relationships over 6 biome types (Aragão *et al.* 2005; Cohen *et al.* 2006; Fensholt *et al.* 2004; Garrigues *et al.* 2008; Privette *et al.* 2002).

2.2.2.3 MODIS-LAI product processing

Images obtained using the main algorithm are preferred for several reasons: the back-up NDVI-based algorithm is not sensitive to data input uncertainties (Yang *et al.* 2006a). This algorithm is also very specific to biome type and therefore does take into account vegetation variability (Yang *et al.* 2006a). Furthermore, if biomes are misclassified, the biome-dependent LAI products become inaccurate (Yang *et al.* 2006a). LAI products obtained from the back-up algorithm are usually extracted under sub-optimal conditions (e.g. cloud cover) and are therefore not recommended for validation studies (Yang *et al.* 2006a).

The distinction between images obtained with the main algorithm and those obtained with the back-up algorithm was achieved using the MODIS Land Data Operation Product Evaluation (LDOPE) tools. MODIS pixels contain information stored in 8-bit layers. The LDOPE tools unpack the 8-bit layers in a MODIS pixel; layer 0 contains the information about the algorithm used in the processing of the pixel. Only pixels that were obtained using the main algorithm were used for analysis. After all images were selected for main algorithm use, the LAI values were extracted from the images for comparison to the *in situ* LAI values.

2.2.3 In situ and satellite-based phenological analysis

The temporal phenological analysis of the forest was conducted using TIMESAT (Jönsson and Eklundh, 2002; 2004).This software program obtains seasonality information from time-series satellite data by adapting a Savitzky-Golay filtering function to determine phenological parameters such as the number of growing seasons, the Start-of-Season (SOS), the End-of-Season (EOS) and Length-of- growing Season (LOS) (Jönsson and Eklundh, 2002; 2004). This program was used to assess whether MODIS-LAI products have similarities or differences in SOS, EOS and LOS to *in situ* values. Furthermore, if the products were different, the program was used to establish the main factors contributing to these differences.

To quantify any similarities or differences between LAI measurements, MODIS-LAI values were directly compared through ordinary least square linear regression and correlation analyses to *in situ* data values for the 2008-2010 growing and the dry seasons in each successional stage. When comparing the LAI values between *in situ* and MODIS-LAI products, the *in situ* values were used as the reference as they were believed to be the most accurate due to their smaller scale and greater flexibility for data collection. Root Mean Square Error (RMSE) was also calculated to determine the size of errors within a regression.

Lastly, the Wilcoxon rank sum test was used to quantitatively compare differences between LAI and WAI values between seasons and to make climatological comparisons between growing seasons. This test is often used to make comparisons between two variables where the null hypothesis states that the median difference between pairs of observations is zero.

3. RESULTS

3.1 Seasonal variation of *in situ* and MODIS LAI time-series

In situ LAI values were compared to MODIS-LAI products through time-series analysis as a function of successional stage, showing the phenological patterns from 2008-2010 for three (early, intermediate, late) successional stages.

The early successional stage time-series shows a cyclical sinusoidal trend with a synchronized pattern of increases and decreases for both MODIS and *in situ* values (Fig. 3a). In general, the MODIS-LAI products in the early successional stage are overestimates. The only exception occurs during growing season 1 (2007-2008) and season 3 (2009-2010) where MODIS-LAI values were underestimated by a value of 1 and 0.4 respectively. The growing season 2 (2008-2009) is significantly overestimated by the MODIS-LAI products by a value of 1.5and is also the season with the greatest amount of overestimation. The beginning of growing season 4 (2010-2011) contains many fluctuations of LAI values from both the *in situ* data and the MODIS-LAI products. No overestimation occurs during this season as both the *in situ* values and MODIS values peak at 5.1 and 4.8 respectively.

The intermediate successional stage time-series differs from the early successional stage in that there is much less overestimation by MODIS (Fig. 3b). Unlike the early stage, a very close synchronicity is apparent between *in situ* values and MODIS-LAI products. However, MODIS data continues to underestimate *in situ* values during peak LAI as in the early successional stage. MODIS underestimates *in situ* LAI values at the beginning of growing season 1 (2007-2008) (Jan 9, 08), with values of 2.3 versus estimates of 4.6 by *in situ* measurements. In addition, MODIS also underestimates *in situ* LAI values at the beginning of growing season 2 (2008-2009) by a value of 1.1. During the peak of growing season 2 LAI values are underestimated by MODIS by 3.4 units. Likewise, during the mid-growing season 2 MODIS underestimates LAI by a value of 1. The beginning of growing season 3 (2009-2010) however (Nov 17, 10), is characterized by overestimations by MODIS by a value of 1.5. In contrast, the dry season demonstrates closer relations between MODIS and *in situ* values as well as synchronicity for the beginning and end of the growing season for both seasons.

The late successional stage time-series, like the early and intermediate stages, also shows cyclical sinusoidal patterns (Fig. 3c). During growing season 1 (2007-2008), MODIS and *in situ* LAI increase and decrease in synchronized patterns. At peak LAI increase, MODIS overestimates *in situ* LAI values by 0.9 and 0.4. Privette *et al.* (2002) also identified this pattern, determining that MODIS-LAI values were lower during the wet season and larger than the *in situ* values during the dry season. At the lowest values, MODIS underestimates LAI by 0.3. Similarly, growing season 2 is highly overestimated by MODIS-LAI products with a peak LAI value of 3, whereas *in situ* estimates of peak LAI value were 1.6. In growing season 3 (2009-2010) many fluctuations occurred and every peak was lower than the previous one where under/overestimation was minimal with values of 0.3 and 0.9 respectively. These values are deemed to be reasonable as evidenced by Privette *et al.* (2002) who identified MODIS-LAI values to be 0.3 units lower in the growing season and 0.1 units higher in the dry season.

The early, intermediate and late successional stage time-series values were then integrated into a single time-series. The trend in the integrated time-series values can be described as a cyclical, sinusoidal function (Fig. 3d). The time-series values show that LAI has a strong seasonal variation with the peak of the growing season showing the highest variability and highest LAI values as was also evidenced by a study conducted by Privette *et al*. (2002).

In this integrated time-series graph, it is observed that in general the seasonal dynamics of MODIS-LAI illustrated in the time-series is roughly similar to the *in situ* LAI values, which demonstrate the increase of LAI from the growing season of 2009 to 2010 (Fig. 3d). Fensholt *et al.* (2005) encountered a similar observation when comparing *in situ* LAI values to equivalent MODIS-LAI products in a time-series graph for a semi-arid, tropical biome.

MODIS-LAI values overestimate the *in situ* LAI data values for all three years, particularly for the growing season. The MODIS peak growing season value over all three seasons is estimated to be 6.6 whereas peak *in situ* LAI is 5.5. In addition, the time-series graph shows high LAI fluctuations throughout both growing seasons. This was also observed in a study conducted by Morisette *et al.* (2006), who detected wild LAI fluctuations very similar to the time-series graphs shown in this study between and within seasons, even in two consecutive dates.

When analyzing the time-series by growing season, it is evident that during growing season 1 (2007-2008), MODIS follows a similar pattern of leaf growth to that of the *in situ* data but is generally one unit higher (Fig. 3d). Although growing season 2 (2008-2009) had the lowest overall LAI values, it also had high degrees of overestimation at the beginning of the season (Dec 26, 08). The peak LAI value for the *in situ* measurements during growing season 2 was 3.5 whereas the peak LAI for MODIS was 5.8. Overestimation is also apparent for the minimum values estimated by MODIS in the growing season which is 2 for MODIS and 1 for the ground data. The growing season 3 (2009-2010) (Fig. 3d) had high degrees of fluctuation. The maximum peak value for the ground data is 5.5 whereas the MODIS value is 6.5. The greatest discrepancies occur twice during the season: high underestimation during the beginning of the growing season (Nov 25, 09) where the *in situ* value is 5.3 and the equivalent MODIS value for the same date is 1.7, and again during mid-season (March 6, 09) for the minimum values where the minimum *in* situ value is 1.89 and the minimum MODIS-LAI value is 0.5; a value only expected during the dry season.

3.2 Quantifying MODIS-LAI product agreement to *in situ* LAI values as a function of successional stage through regression analysis

The strength of the relationship of *in situ* LAI to MODIS-LAI in the early successional stage is moderately strong (P= $1E^{-4}$; r^2= 0.64; RMSE= 0.87), which is also demonstrated in the regression analysis (Fig. 4a). All but 3 points lie above the 1:1 line, indicating that the majority of the values in this successional stage are overestimated. Furthermore, the fact that the line approaches the 1:1 line as LAI values increase shows that the accuracy by MODIS increases with increasing LAI values.

The error of the data values within the regression was calculated using the Root Mean Square Error (RMSE). The RMSE measures the distance data points fall above or below the regression line. As a result, RMSE is analogous to the standard deviation of the average. The significance of the RMSE can be measured by the closeness of the points to the regression line versus the closeness of the points to the average of the Y values in the regression. The distance of the data points to the average of the Y values can be calculated as the standard deviation of Y. Therefore, if the RMSE is smaller than the standard deviation (SD) of the y-axis, it can be said that the values are closer to the regression line than the horizontal line (y-axis). The RMSE for the early successional stage is 0.87 with a SD of Y of 1.04. Although the RMSE is less than the SD of Y, this relationship is described the least accurately by the R^2 values as the points digress the greatest distance from the regression line.

In the intermediate successional stage (Fig. 4b), the distribution along the 1:1 line shows that the lower LAI values are overestimated by MODIS while those that are in the higher end, presumably the peak LAI values, are underestimated by MODIS. Although the intermediate stage time-series analysis demonstrated much higher synchronicity between *in situ* values and MODIS-LAI products, the intermediate stage displayed a lower correlation than the early successional stage. The RMSE in the intermediate stage was lower than the early stage with a value of 0.53 and the SD of Y of 0.80. However, because the RMSE is much smaller than the SD of Y compared to the early successional stage, this indicates that there are fewer differences between the two LAI estimates than in the early successional stage.

The late successional stage has the highest accuracy of LAI estimations. Although there is evidence of overestimation by MODIS, the fact that the late successional stage regression line is closest to the 1:1 line shows that the overestimation is also lower than for the early and intermediate successional stages (Fig. 4c). In contrast to the intermediate successional stage, the accuracy between minimum LAI and maximum LAI within a season are very similar, as evidenced by the evenness of the regression line as it approaches the 1:1 line in both the lower and higher LAI values. This was also observed in a study by Fensholt *et al.* (2004), where the regression between *in situ* and MODIS-LAI products had an R^2 value of 0.81 with a slope close to the 1:1 line for a semi-arid tropical environment. The late successional stage also seems to have the smallest differences between LAI estimates as evidenced by an RMSE value of 0.47. In this case, the SD of Y equals 1.29, suggesting that the LAI values correspond closely to the regression line.

The integrated regression analysis shows a moderate-to-high correlation between the MODIS-LAI and *in situ* values (Fig. 4d). The fact that the majority of the data values lie above the 1:1 line suggests that the majority of the MODIS-LAI values are overestimates, as was evident in the time-series analysis. The RMSE for the cumulative data is 0.63, while the SD of Y is 1.07. Because RMSE is less than the SD of Y, the integrated regression analysis demonstrates that between the two LAI estimates is accurately described by the R^2 value.

Because of the large discrepancies between *in situ* and MODIS LAI in season 2 (2009-2010) for all successional stages, an additional analysis was conducted to determine if these discrepancies were due to measurement error. Therefore, the SD of *in situ* values was calculated for season 2 and season 3 (2009-2010) for each successional stage. These calculations were done in order to assess the variation of the *in situ* measurements between seasons, thereby determining the accuracy between the two seasons. The results consistently show that the SD for season 2 is less than the SD for season 3 in all three successional stages (Table 1). In particular, the measurement error for season 2 in the early successional stage is 0.79 (mean) ± 0.5 SD, whereas the season 3 measurement error was 2.1 (mean) ± 1.9 SD. Therefore, it is evident that season 3 measurement errors were higher than those of season 2; which in turn suggests that the quality of the dataset for season 3 was poorer than season 2.

3.3 Validation of MODIS Woody Area Index products using hemispherical photographs

It has been widely stated in the literature that areas of low LAI are correctly measured by MODIS (Yang, 2006; Fensholt *et al*. 2004; Cohen *et al*. 2006; Morisette *et al.* 2006; Privette *et al*. 2002). It is therefore hypothesized, that because of this property, it is possible for MODIS-LAI products to measure WAI in tropical dry forests. In order to evaluate this hypothesis, *in situ* WAI values were compared to MODIS-WAI products by making direct correlations for the sites. Only dates within a 2-day difference between satellite and *in*-situ collection were used for comparison.

3.3.1 Assessing agreement between in situ WAI and MODIS-LAI dry season values through regression analysis

The early successional stage has a moderate correlation between *in situ* WAI and MODIS-WAI (Fig. 5a); however, the linear regression of *in situ* and MODIS-WAI products is significant (r^2= 0.48; P= $4E^{-5}$). The majority of the clustering occurs at the lower values between x= 0.5 and y= 1 along the y axis. The fact that the regression line lies above the 1:1 line demonstrates that MODIS-WAI products overestimate *in situ* values in the early successional stage.

The RMSE of the regression line is 0.70, and although this is a relatively low value, the SD of Y was calculated to be 0.56. This suggests that the relationship of the LAI values around the regression line is not as strong as the one to the Y-axis; therefore there is only a marginally strong relationship between the two WAI estimates.

The intermediate and late successional stage results are slightly different (Fig. 5b and c). The correlations between *in situ* and MODIS-WAI products for the intermediate successional stage increases (r^2= 0.57) while that of the late successional stage is lower (r^2 =0.45) with both correlations showing a statistical significance of P= $2.16E^{-6}$ and P= $0.1E^{-4}$ for the intermediate and late stage, respectively. Some clustering is still evident around the lower values, and more values appear directly on the 1:1 line, especially in the intermediate stage. In addition, there is slightly more dispersion over the y-axis than the x-axis for all the graphs, suggesting the MODIS-WAI products provide less reliable measurements than *in situ* values.

Akin to the LAI analysis, the early, intermediate and late WAI values were integrated into a single correlation analysis. When all three integrated successional stages are analyzed, clustering is evident among the lower WAI values (Fig. 5d). Although the relationship is moderately weak, the correlation analysis shows the relationship is statistically significant (r^2= 0.35, P= 7.67^{-10}). The fact that more variance occurs along the y-axis indicates that the variance is caused by the MODIS-LAI products as opposed to by the *in situ* values. In addition, the RMSE values are relatively low at 0.49. However the SD of Y is 0.46 indicating that the WAI values digress from the regression line slightly more than the WAI values digress from the Y axis.

3.3.2 Quantifying measurement accuracy between in situ WAI and MODIS-LAI dry season values

A Wilcoxon Rank Sum test was performed to assess differences in WAI measurements between *in* situ and MODIS for each successional stage. When the range of the data collection is plotted (Fig. 6a), the Wilcoxon rank sum test shows that there are statistically significant differences between *in situ* and MODIS-WAI products for the early successional stage (H= 20.578, df= 1, P= 5.73E^{-6}). Furthermore, when these differences are compared within each of the three years, significant differences remain between the two WAI estimates for each dry season (2008: H= 9.344,df= 1,P= 2E^{-3}; 2009: H= 10.93,df= 1,P= 9E^{-4}; 2010: H= 4.685,df= 1,P= 3E^{-2}) (Fig 6b).

Unlike the early stage, the intermediate successional stage has a marginally significant difference between the *in situ* and MODIS-WAI products when the dataset includes all three years (H= 3.937, df=1, P= 4.8E^{-2}) (Fig. 7a). In addition, the RMSE revealed a low value of 0.33 and the SD of Y= 0.4, indicating a stronger relationship than that of the early successional stage.

However, when the dataset is separated and the WAI estimates are compared between each season (Fig. 7b), no significant differences exist between the *in situ* and satellite WAI values (2008:H= 1.875,df= 1,P= 1.95E^{-3}; 2009: H= 1.09,df= 1,P= 3.10E^{-3}, 2010: H= 1.424,df= 1,P= 2.33E^{-3}).

More interestingly, in the late successional stage, when all data values are analyzed cumulatively (Fig. 8a), there is a significant difference between the *in situ* and satellite WAI values (H= 5.997, df= 1, P= 1.4E^{-2}). However, when the two WAI estimates are compared within each year (Fig. 8b), Wilcoxon analysis shows no significant differences between the *in situ* and satellite WAI for any of the three years (2008: H= 3.931,df= 1,P= 5.3E^{-2}; 2009: H= 2.26,df= 1,P= 1.33E^{-3}; 2010: H= 0.707,df= 1,P= 4E^{-1}). The RMSE was calculated to be 0.34 with a SD of Y= 0.36. Because the difference between the two numbers is small and the SD of the MODIS values is larger than the RMSE, this suggests that the relationship of the WAI values around the regression line is as strong as the one to the Y-axis, therefore the relationship between the two WAI index estimates can be marginally described by the regression line.

An additional analysis was conducted to demonstrate how climatic differences could affect differences in WAI measurements between each dry season. Specifically, to test whether temperature, soil moisture and humidity differences between dry seasons could have contributed to tree mortality in each successional stage. Therefore, Kruskall-Wallis tests were performed to test the climatic influence for each environmental variable between the 2008, 2009 and 2010 dry seasons at each successional stage. The results show that with the exception of soil moisture in the intermediate stage, each climatic variable showed significant differences between the years 2008, 2009 and 2010 (Table 2).

3.4 Comparison of *in situ* and MODIS phenological patterns

The phenology and seasonality for both the *in situ* and MODIS time-series were analyzed with TIMESAT (Jönsson and Eklundh, 2002; 2004); a program that extracts seasonal parameters such as number of growing seasons, Start-of-Season (SOS), End-of-Season (EOS), and Length-of-Season (LOS) for satellite products using a Savitzky-Golay function and 10% of amplitude threshold (Jönsson and Eklundh, 2002; 2004).

3.4.1 Start of Season (SOS)

Overall comparisons of *in situ* values to MODIS-LAI products reveal that MODIS detects SOS earlier than *in situ* measurements (Table 3, Fig. 9). Comparing MODIS and *in situ* SOS estimations for each successional stage suggests that for the early and intermediate stage, MODIS estimated SOS 1-2 weeks earlier than *in situ* values. This difference in estimates is much longer for the late stage, ranging from 2 weeks to 1 month earlier than *in situ* values (Table 3, Fig. 9).

Furthermore, comparing each instrument's SOS estimates between season 1 and season 2 allowed elucidation of the ability of each instrument to estimate SOS consistently. The analysis shows that MODIS captures SOS in season 1 and season 2 within 9 days in all 3 successional stages, as opposed to *in situ* values which differ in estimations from season 1 to season 2 at a range of 2-3.5 weeks (Table 3, Fig. 10).

To determine if the 2-3 week time lag of *in situ* SOS estimates between season 1 and season 2 was due to local climatic factors, a Wilcoxon analysis was used to determine the differences in soil moisture levels between season 1 (2008-2009) and season 2 (2009-2010). Wilcoxon analysis demonstrated significant differences in moisture levels between season 1 and season 2 for all 3 successional stages (Fig. 11). Given the changes in soil moisture recorded it can also be deduced that rainfall patterns changed from season 1 to season 2.

To further corroborate this assertion, the *in situ* time series was superimposed to the soil moisture time series for the same years. If soil moisture is considered a proxy for rainfall, it is evident that SOS closely coincides with the onset of rainfall in both season 1 and season 2, with season 2 rainfall occurring later than season 1 (Fig. 12).

3.4.2 End of Season (EOS)

Unlike the SOS, *in situ* data estimates EOS before MODIS except for season 1 (2008-2009) in the intermediate and late successional stages (Table 3, Fig. 9). The differences in estimates between the *in situ* values and MODIS are large, especially in the early successional stage and during season 2 (2009-2010) in all successional stages (Table 3, Fig. 9).

Contrasting each instrument's ability to estimate EOS consistently between season 1 and season 2 reveals that MODIS is once again more consistent in predicting

EOS than *in situ* values, particularly for the intermediate and late stage (Table 3, Fig.10). MODIS estimates of EOS were conducted on the same dates, and the early stage had a discrepancy of only 8 days. In contrast, the shortest time lag for *in situ* values to determine EOS between season 1 and season 2 is 2 weeks in the early successional stage. These estimates successively increase to 23 and 29 days for the intermediate and late successional stages respectively (Table 3, Fig.10).

In order to determine if the approximate 26 day EOS time lag between seasons was due to increases in leaf growth during season 2, a Wilcoxon analysis was performed on LAI distribution values between season 1 (2008-2009) and season 2 (2009-2010) (Fig. 13). Test results show significant increases in LAI between season 1 and season 2 for all three successional stages (Early: H= 6,df=1,P= 1.4E^{-2}; Intermediate: H= 4.89,df= 1,P= 2.7E^{-2}; Late: H= 9.281;df= 1,P= 2.3E^{-3}) suggesting an increase in leaf growth from season 1 to season 2.

3.4.3 Length of Season (LOS)

Similar to SOS and EOS, estimates of LOS remain constant between seasons in terms of MODIS values. The early and late stages in season 1 and season 2 as well as season 2 of the intermediate stage have a LOS of 237 days. Season 1 of the intermediate stage has a LOS of 245 days. In contrast, *in situ* values show slightly less consistency than MODIS values, all estimating LOS within approximately 12 days for each season with the exception of season 1 of the intermediate stage which varies estimates of LOS between season 1 and season 2 by 43 days (Table 3).

4. DISCUSSION

4.1 Seasonality variation of *in situ* and MODIS LAI time-series

4.1.1 Effects of vegetation heterogeneity, scaling differences and viewing angle on MODIS-LAI product agreement to in situ LAI values

The time-series described in this study were predominantly cyclical-sinusoidal, which are the primary components of most seasonal time-series trends (StatSoft, 2011). Generally, MODIS overestimates *in situ* LAI values for all three years especially during the growing season. This has been documented in previous studies of MODIS overestimation over broadleaf deciduous forests (Abuelgasim *et al.* 2006; Garrigues *et al.* 2008; Morisette *et al.* 2006; Sprintsin *et al.*2009). Huemmrich *et al.* (2005) has also found strong relationships between ground-measured LAI and MODIS-LAI with the MODIS-LAI displaying slightly higher values than ground LAI. However, as of present the effects of MODIS-LAI estimation in tropical dry forests have not been investigated.

MODIS overestimations were observed for all three successional stages as evidenced by the regression values (Fig. 4). The early successional stage showed high degrees of overestimation especially around lower LAI values (Fig. 3a,4a). Similarly, in the intermediate successional stage the same observation holds true: as LAI decreases towards lower values MODIS products are overestimated (Fig. 3b,4b). Furthermore, although the evenly distributed points along the 1:1 line suggest less bias regarding over or underestimation in the late successional stage, the fact that the regression line falls slightly above the 1:1 line indicates that MODIS-LAI products still have a bias towards overestimation (Fig. 4c).

There are several reasons as to why MODIS values overestimate *in situ* data values. Firstly, in areas where no dominant land cover is present, the lower resolution of MODIS-LAI values causes different vegetation types to be present in a single pixel thereby creating errors in estimation (Tian *et al.* 2002). This is certainly evident in PEMS where the majority of plot sites that fall within a MODIS pixel also share other types of vegetation. Garrigues *et al.* (2008) states that most LAI retrieval algorithms are non-linear and are calibrated at the patch scale, hence when applied over vegetation with heterogeneous landscapes the moderate resolution pixels can introduce a scaling bias that can reach up to 50% of the actual LAI value.

Also, the viewing angle of both instruments creates a scaling issue because vertical heterogeneity at the landscape scale is able to amplify LAI reflectance signals due to the presence of the understory (Garrigues *et al.* 2008). *In situ* LAI measurements conducted with the LAI-2000 removes understory reflectance by measuring 1m above ground level. This contrasts with MODIS-LAI products which measure LAI from nadir, enabling MODIS to capture the canopy as well as understory leaf reflectance (Soudani *et al.* 2006). The fact that understory layers can be denser than canopy layers (Ni-Meister *et al.* 2010; Soudani *et al.* 2006), further contributes to LAI overestimation during the growing season (Garrigues *et al.* 2008).

For example, as the canopy decreases in foliage in the intermediate successional stage, *in situ* measurements capture foliage loss from the canopy. However, because the intermediate stage has dense understory vegetation and contains lianas which retain leaves for longer periods than a canopy tree (Putz, 1990; Kalácska, 2005b; Sánchez-Azofeifa *et al.* 2009), it is plausible that the overestimation of values in the MODIS-LAI products may be exacerbated.

Lastly, since reflection of light from vegetation is scale-dependent, the satellite viewing angle and canopy structure can also affect leaf reflectance by incorporating background reflectance values into the signal (Asner, 1998). Due to vertical heterogeneity, clumping of vegetation creates gaps which expose litter, woody material and bare soil to nadir-looking satellites. The coarser the satellite resolution, the greater the reflectance contribution from background elements (Asner, 1998; Fensholt *et al.* 2004; Myneni *et al.* 2002) is to be expected. Therefore, peaks in the MODIS satellite time-series graphs (such as those represented in Figure 3), are likely affected by the presence of understory, as well as the background material within the MODIS pixel. Furthermore, time-series containing the integrated values of all 3 successional stages clearly demonstrates phenology patterns equivalent to the *in situ* time-series but with overestimation of LAI values (Fig. 3d) is also expressed in the correlation graphs (Fig. 4d). Therefore, all of the aforementioned contributions to reflectance could serve to erroneously augment LAI reflectance values in the examples above (Asner, 1998; Chen *et al.* 1997; Garrigues *et al.* 2008).

4.1.2 Effects of stand heterogeneity on MODIS-LAI estimates

One distinct observation in this study was the manner in which the accuracy between *in situ* LAI and MODIS-LAI estimates was affected by the heterogeneity of the plot stands: the more heterogeneous the stand, the less accurate the MODIS-LAI estimates.

The heterogeneity of a plot produces higher inaccuracies for LAI estimations by creating variations in surface reflectance data, in turn causing errors in satellite LAI measurements (Tian *et al.* 2002). The early successional stage plot is characterized as having many canopy gaps compared to the intermediate and late stages (Kalácska *et al.* 2005b). The early successional stage also produced the lowest correlation between *in situ* values and MODIS-LAI products of all the successional stages (Fig. 4a). The RMSE of 0.87 and a SD of Y of 1.04 confirm that the early successional stage had the weakest relationship between the *in situ* and MODIS LAI estimates. This low correlation is likely due to the heterogeneity of the early successional stage forest stand (Kalácska *et al.* 2005b).

Garrigues *et al.* (2008) hypothesizes that the lack of correlation observed in heterogeneous plot stands arises as a result of LAI algorithms being non-linear and calibrated at the patch scale. Therefore, applying the algorithm to heterogeneous canopies introduces a scaling bias on LAI estimates. This in turn causes less agreement between *in situ* LAI and the MODIS-LAI satellite products in more heterogeneous successional stages.

The effects of plot heterogeneity are also observed in the late successional stage (Fig. 4c). The late successional stage is largely homogeneous in vegetation content while having the highest correlations of *in situ* LAI values to MODIS-LAI products in comparison to all other successional stages (r^2= 0.88; p= 2.86E^{-10}). Such observations suggest that the homogeneity, of the stand plays an important role in the accuracy of the MODIS-LAI estimates (Garrigues *et al.* 2008; Tian *et al.* 2002).

An interesting anomaly which was found among the data was that season 2 (2008-2009) had the lowest productivity as characterized by *in situ* LAI values and also had the highest overestimation by MODIS in all 3 successional stages. Therefore, the season 2 and season 3 *in situ* dataset was evaluated for measurement quality by calculating and comparing the standard deviation (SD) of the *in situ* values for season 2 and season 3 in each successional stage. Only two seasons were used as these were the only seasons with a complete cycle in the time-series.

The results demonstrated that there was more error propagation in the season 3 dataset than in season 2 as depicted by the larger SD of the mean in season 3 than in season 2, consistently for all three stages (Table 1). Aside from measurement error, additional factors may influence season 2 MODIS-LAI estimates such as the presence of understory (Asner, 1998; Chen et al. 1997; Garrigues *et al.* 2008; Pisek, 2010), the nadir viewing angle of MODIS which captures understory growth that occurs before canopy growth (Richardson and O'Keefe, 2009), and finally increases in soil moisture (SM) values.

LAI products have a close relationship with SM patterns for each successional stage (Fig. 12b). For example, intermediate successional stage MODIS overestimation in season 2 is lower than the early and late stage overestimation in season 2. Similarly, SM patterns during season 2 are lower than the early and late stage (Fig. 12b). The relationship between LAI and SM is most markedly shown during mid-growing season 2 (2008-2009) (Fig. 12b): a sharp decrease in soil moisture values correlates with a sharp decline in both *in situ* and MODIS-LAI products.

Similar to the anomaly of high MODIS-LAI overestimation during season 2, it is also evident in the beginning of season 4, that there are unrealistically high MODIS-LAI estimations occurring on the same date in all three successional stages (Fig. 3). Much like in season 2, these high MODIS-LAI estimations also coincide with sharp increases in SM on similar dates (Fig 12).

These spikes in MODIS-LAI values could be attributed to obtaining LAI reflectance values under saturation conditions. Indeed, since this period is the time of maximum foliage production. At this MODIS-LAI value of 4.4 in the early and late successional stage and 3 in the intermediate successional stage, the MODIS algorithm becomes less sensitive to reflectance and creates erroneous and overestimated LAI products (Garrigues *et al.* 2008; Myneni *et al.* 2002).

4.2 Validation of MODIS Woody Area Index products

4.2.1 Effects of quantity of woody material on MODIS-WAI estimates

The results from the correlation analysis demonstrate that as the woody components of a forest increase, so does the accuracy between MODIS-WAI and *in situ*

WAI. In the present study, the intermediate stage has the highest correlation between *in situ* WAI and MODIS-WAI products (Fig. 5b).

A study by Sánchez-Azofeifa *et al.* (2009) concluded that the presence of lianas largely influences WAI values in tropical dry forests. In PEMS, the presence of lianas has been documented for the intermediate and late stages (Kalácska *et al.* 2005a; Madeira *et al*. 2009, Sánchez-Azofeifa *et al.* 2009). The intermediate stage is considered to be particularly dense due to its understory composition of young trees and lianas (Madeira *et al.* 2009) and is the only successional stage with such a dense understory. The presence of lianas and the dense understory in the intermediate stage creates a higher density of woody materials, which suggests it is more easily detected by the MODIS satellite as evidenced by higher correlations.

Mean WAI also increases with increasing succession. That is, the majority of the contribution to WAI in early successional forest stands is through young trees whereas a significant contribution of the intermediate and late successional stages to WAI is through lianas (Kalácska *et al.* 2005b; Sánchez-Azofeifa *et al.* 2009). Such a distribution of WAI contributions contributes to lower WAIs in early successional stages (mean WAI-HP: 0.54, mean MODIS-LAI: 1.10). In contrast, in the intermediate and late stages the presence of lianas contribute to an increasing WAI (mean WAI-HP: 0.63, mean MODIS-WAI: 0.82; mean WAI-HP: 0.73, mean MODIS-WAI: 0.94 respectively). These results are also supported by a study conducted by Sánchez-Azofeifa et al. (2009), which observed increases in WAI with increasing successional stage as a function of canopy openness, which is a determining characteristic for the presence of lianas. Since canopies are more open in the intermediate successional stage in comparison to the late successional stage, there is a higher presence of lianas and understory species and therefore higher WAI values are observed.

4.2.2 MODIS-WAI product accuracy compared integrally and between seasons to in situ WAI

When comparing the ability of MODIS-WAI products to measure WAI in different successional stages, it is evident that for the early successional stage there are significant differences between the two estimates. This remains true when all data is accumulated among the three years, as well as when compared for each dry season (Fig. 6a and b). There may be a few explanations for this occurrence: firstly, an early successional forest is composed of an abundance of heterogeneous vegetation (Madeira *et al*. 2009, Sánchez-Azofeifa *et al*. 2009), which in turn creates a heterogeneous canopy structure. Canopy heterogeneity occurs at two different scales: vertically and horizontally (Ni-Meister *et al.* 2010). Vertical heterogeneity occurs due to the forest's varying distribution of trees, with more trees present in the middle portion than at the top or the bottom (Ni-Meister *et al*. 2010). Horizontally, clumping occurs both inside the canopy at the stem level and at a larger scale outside the canopy with tree crowns (Ni-Meister *et al*. 2010). Therefore, the differences in measurement at an early successional stage could be attributed to differences in scale. That is, hemispherical photographs are obtaining information from a tree scale within the forest, and therefore measuring horizontal heterogeneity. In contrast, MODIS-LAI products are measured at the 1-km scale and therefore measure both vertical and horizontal heterogeneity using canopy reflectance.

An early successional stage forest, as suggested by Sánchez-Azofeifa *et al*. (2009) is more open than either the intermediate and late stage forests. Because of this property, the understory of an early successional stage forest has a larger impact on the light reflectance of the stand where differences in the spectral signatures between leaf and soil background are very prominent (Pisek *et al.* 2010). It has also been suggested that vegetation indices are sensitive to soil background, especially in areas of low LAI (Darvishzadeh et al. 2008). Darvishzadeh *et al.* (2008) found that the contrast between leaves and soil determine the strength of the relationship between reflectance and LAI. Specifically, the higher the contrast between the leaves and the ground, the stronger the relationship is between light reflectance and LAI. This is also a factor that influences reflectance of the early stage that does not necessarily occur in the intermediate because of understory cover due to lianas, and in the late stage because it is composed of tall, mature trees that have closed this canopy gap.

For the intermediate and late stages however, it is hypothesized that climatic differences between each dry season caused either the growth or loss of nonphotosynthetic biomass that was apparent in the dry season for the following year. This growth or loss caused significant differences between *in situ* and MODIS-WAI measurements to be apparent when the data were integrated for all three years (Fig. 7a and 8a respectively) but not when measurements were separated and compared within each dry season (Fig. 7b and 8b respectively).

To corroborate this theory, three different climatic variables were examined for each successional stage: temperature, soil moisture and humidity. The results demonstrated that with the exception of soil moisture in the intermediate stage, each climatic variable showed significant differences between each 2008, 2009, 2010 years (Table 2). Therefore, it is plausible to assume that these yearly climatic differences could cause either the growth or loss of trees as a response either to changes in temperature or water availability to the trees. Neither season is comparable to the one previous nor preceding it because each forest stage is undergoing constant ecological changes. These ecological changes are captured in this study as microclimatic changes and differences in tree growth or loss between seasons, expressed as increasing WAI values.

When these dynamic measurements of tree growth are compounded together in an integrated dataset covering three years, comparisons between instruments may demonstrate statistically significant differences between measurements. However, the fact that there are no statistically significant differences between the measurements when compared for a singles season, suggests that MODIS-WAI products could potentially be used to estimate WAI in broadleaf dry successional forests where woody area density is high.

4.3 Comparison of *in situ* and MODIS phenological patterns

4.3.1 Start of Season

Comparison of *in situ* methods to MODIS-LAI products demonstrates that MODIS detects SOS sooner than *in situ* measurements (Table 3, Fig. 9). For the early and intermediate stage, MODIS estimates SOS 1-2 weeks before *in situ* values (Table 3, Fig. 9). However, the difference in estimates for the late stage is much longer, ranging from 2 weeks to 1 month before *in situ* values (Table 3, Fig. 9). The fact that MODIS is generally the first to identify SOS may be due to understory effects. Usually, the canopy produces leaf flush later than understory vegetation (Richardson and O'Keefe, 2009). Therefore, because the LAI-2000 only measures canopy LAI values, it can only capture the delayed canopy leaf flush. In contrast, MODIS is able to capture understory leafing which leads to identifying forest greening before *in situ* values (Ahl *et al.* 2006). The fact that MODIS estimates SOS within 9 days in season 1 (2008-2009) and season 2 (2009-2010) for all three successional stages, also suggests that understory phenology is being captured and the estimates are not a result of an algorithm estimation error. Furthermore, Ahl *et al.* (2006) also concluded that MOD15 LAI products determine SOS sooner than *in situ* measurements, suggesting that understory effects create these phenological shifts.

In addition, the fact that MODIS SOS estimations only deviate 9 days between season 1 and season 2 for all three successional stages relates to the fact that MODIS products are collected as 8-day composites. Any phenological change within the 8-day composite period will manifest as a change 8 days later. This is in contrast to *in situ* values which differ in estimations from season1 to season 2 at a range of 2-3.5 weeks (Table 3,

Fig. 10). This large variation in the estimations of *in situ* values between seasons could be due to climatic factors. For each successional stage, there is a significant difference between soil moisture measurements from the first season to the second season. Such differences indicate that rainfall patterns also changed from the first season to the second season thereby causing changes in phenology (Fig. 11).

This is also evident when the *in situ* time-series values are superimposed to soil moisture time-series for the corresponding years (Fig. 12a,b,c). The high synchronicity between soil moisture and leaf growth indicates that soil moisture had a great effect on *in situ* canopy phenology patterns which may not affect MODIS phenology as drastically due to differences in scale. Ultimately, this observation provides an insight into the 2-3 week lag difference between *in situ* values and MODIS data. If soil moisture is considered as a proxy for rainfall, it is evident that local rainfall events changed from season 1 to season 2, with the rainfall for the second season occurring sooner than the first season (Fig. 12 a,c).

However, in contrast to the early and late stage, the intermediate successional stage SOS season 2 begins later than in season 1 (Table 3, Fig. 10). This could be due to the same meteorological changes; SM distribution in the intermediate stage was significantly lower than the early and late successional stage (Fig. 11). In addition, the soil moisture time-series (Fig. 12b) demonstrates that soil moisture peaks for season 2 coincide with the SOS LAI peaks; suggesting that SOS for the intermediate stage began later than season 1 because of a difference in the commencement of rainfall within these plot stands.

4.3.2 End of Season

In contrast to the SOS, *in situ* values estimate EOS sooner than MODIS values with the exception of season 1 (2008-2009) in the intermediate and late successional stages (Table 3, Fig. 9). These differences in estimates are large, especially in the early successional stage and for season 2 (2009-2010) in all successional stages (Table 3, Fig. 9). This could again be attributed to the scaling factor of MODIS versus the *in situ* values. The EOS threshold in the TIMESAT software program is a reduction of LAI to 10% of the amplitude of the seasonality curve (Jönsson and Eklundh, 2002). However, because of the large amount of vegetation contained within a MODIS pixel, the time required for LAI reduction to this value is delayed, especially in heterogeneous areas where different plants have different phenological patterns (Ahl *et al.* 2006; Kalácska *et al.* 2005b). In addition, understory effects may play an additional role in delaying the EOS signal. This is because the intermediate and late stages of the forest contain lianas. Lianas have deeper root systems than the surrounding trees and their architecture increases their ability for water storage (Kalácska *et al.* 2005b). In fact, only once the canopy has lost 30% of its biomass do lianas begin to lose their leaves (Kalácska *et al.* 2005b). Therefore because satellites detect the understory liana phenology, it is likely that the LAI-2000 measuring only canopy, detects EOS sooner than MODIS.

Furthermore, it is equally evident that the differences amplified in the early successional stage are not only due to the scaling differences of both instruments, but also to the heterogeneity of the plots. Early stage plots contain various species of pioneer plants all with their own phenological patterns (Kalácska *et al.*2005b*;* Madeira *et al. 2009*). This would cause more difficulty for the software program to determine the point at which the curve falls to 10% of the amplitude, and ultimately creates larger differences when EOS is determined.

In contrast, MODIS values maintain more consistency in predicting seasonality between season 1 (2008-2009) and season 2 (2009-2010). This is especially evident in the intermediate and late stage, where EOS was estimated on the same dates. Indeed, even in the early stage, which had the largest discrepancy, the difference between season 1 and season 2 is 8 days (Table 3, Fig. 10). However, the same cannot be said for the *in situ* values. In this case, the shortest difference between seasons is 2 weeks during the early successional stage, and gradually increases to larger values in the intermediate and the late stage to a difference of 23 and 29 days respectively (Table 3, Fig. 10).

The fact that there is a difference of approximately 20 days between *in situ* and MODIS EOS estimates, suggests this is the time frame it takes MODIS to detect leaf shedding of the forest stand. The large difference of 29 days in EOS estimation between season 1 (2008-2009) and season 2 (2009-2010) in the intermediate and late stages suggests there was more leaf growth during season 2. This is evident in the time series for both the intermediate and late stages (Fig. 3b and c respectively) where LAI values increase from 2009 and 2010. In addition, it is also evident when comparing the distribution of LAI values of season 1 (2008-2009) to season 2 (2009-2010) (Fig. 13) that a significant LAI increase occurs from the first season to the second season for all three successional stages. Therefore, given the scale at which the satellite views the canopy, the MODIS satellite may require more time to detect leaf loss especially at higher leaf densities.

In addition, there is also a significant climatic difference between season 1 (2008-2009) and season 2 (2009-2010) in soil moisture for the intermediate and the late successional stages (Fig. 9). It is evident that soil moisture significantly increases from the first growing season (2008-2009) to the second growing season (2009-2010). Comparing the rainfall influence to leaf production explains the increase in leaf productivity from one growing season to another. This is because increases in soil moisture associated with higher rainfall and increased water uptake result in higher leaf flush as rainfall is the largest limiting factor for leaf growth in tropical dry forests (Reich, 1984). Ultimately, all these factors combined may have caused the 29 day delay for the end of the growing season in the intermediate and late successional stages.

4.3.3 Length of Season

Although for each season the SOS and EOS change, the LOS (Length-of-Season) does not vary for MODIS values. Both the early, late and season 2 of the intermediate stage have a LOS of 237 days for both seasons (Table 3). Season 1 of the intermediate stage has a longer season by 8 days of 245, which can be deemed negligible (Table 3). However, the *in situ* values vary slightly more than the MODIS values, at approximately 12 days between season 1 and season 2. One exception is season 1 of the intermediate stage which varies by 43 days (Table 3). The fact that this is the only season with such a considerable difference in the length of season, the differences can be deemed as a result of measurement errors for season 2. However, it is important to point out that the difference between season 1 (2008-2009) and season 2 (2009-2010) in the intermediate successional stage with the MODIS values also had the highest difference between seasons at 9 days (Table 3). This would support the fact that there is a difference between the two seasons but may not be as large as it was measured here.

5. CONCLUSION

5.1 Effectiveness of MODIS-LAI products to monitor leaf production in secondary tropical dry forests

The purpose of this study was to determine the accuracy of MODIS-LAI estimates by using MODIS-LAI time-series, to investigate estimates of WAI and phenological patterns in the secondary tropical dry forest of Minas Gerais, Brazil with *in situ* LAI values as a reference.

The analyses in this current study demonstrated the MODIS-LAI product response under a variety of structural conditions (early, intermediate, late successional stages) and types of climatic conditions (dry vs. wet season) over a time span of three years.

Privette *et al.* (2002) determined that the MODIS-LAI algorithm generated reliable values over semi-arid tropical environment in Southern Africa. In addition, the study found that the algorithm accommodated different phenological states and canopy structure. Similar to Privette *et al.* (2002), the time-series observations in this particular study demonstrated the general phenological changes of the tropical dry forest as well as differences in forest structure. However, the accuracy of the MODIS products increased with increasing successional stage and ultimately overestimated *in situ* LAI values in all three successional stages.

This current study also corroborates the findings of Cohen *et al.* (2006), which state that the MODIS-LAI algorithm was found to over-predict in forested biomes and experienced great LAI instability during times that were not related to vegetation change. This was evident in the present study by the growing season LAI fluctuations in all the successional stages.

The current time-series observations demonstrated synchronicity in the phenology of LAI for both the MODIS-LAI products and *in situ* data. Correlation and regression analysis indicated that overestimation by MODIS-LAI occurs in all successional stages. It seems that in TDF's, much like broadleaf deciduous forests (Abuelgasim *et al.* 2006; Garrigues *et al.* 2008; Morisette *et al.* 2006), dryland forest (Sprintsin *et al.* 2009), and Kalahari woodland (Huemmrich *et al.* 2005), MODIS values overestimate *in situ* data, suggesting this is something that requires further investigation.

However, as successional stage increases, so does the correlation between MODIS-LAI and *in situ* data values, suggesting that MODIS-LAI products increase in accuracy with increasing canopy cover and homogeneity. Therefore for TDFs, this would indicate that the most accurate forest monitoring could be conducted in the later stages of tropical dry forests which are coincidently also the plots that require more monitoring as they contribute the most to reducing the effects of habitat fragmentation. Ultimately, MODIS could be used to monitor productivity in late successional areas.

5.2 Using MODIS Woody Area Index products to estimate WAI and liana abundance in tropical dry forests

The correlation analysis for WAI demonstrates that areas with higher woody components are the most accurately captured by MODIS. The intermediate stage in PEMS is characterized as being composed of young trees and lianas (Madeira *et al.* 2009). Sánchez-Azofeifa *et al.* (2009) determined that lianas increase with succession in TDF's. Because the intermediate successional stage has the densest understory due to the presence of lianas, this stage demonstrated the highest correlations between MODIS-WAI and *in situ* WAI. This is presumably because the high density of woody material allows for easier detection. When Wilcoxon tests were performed for *in situ* and MODIS WAI values for each season, no significant differences were found between the two estimates in the intermediate and late stages likely due to the higher density of woody components in the forest. Therefore, this element of the study can be applied to estimate WAI in the intermediate or late successional stages, or to detect the presence of lianas in TDFs through WAI and canopy openness.

5.3 Detecting phenological patterns and seasonality of a secondary tropical dry forest using MODIS-LAI products

This study concludes that because MODIS seasonality time-series identifies the beginning of the growing season before *in situ* values in all successional stages, MODIS-LAI products would be useful for predicting the beginning of the growing season in tropical dry forests for any successional stage. However, early successional stage SOS estimates need to be interpreted cautiously as the heterogeneity of species composition and background light reflectance can be calculated up to one month early and consequently may lead to overestimations. Early and intermediate stages are able to estimate SOS within an accuracy of roughly 2 weeks.

In contrast, EOS estimates would not be beneficial to conduct with MODIS as MODIS-LAI products overestimate EOS by approximately 20 days for the intermediate and late stage, and 30 days for the early successional stage. Clearly, the overestimation of EOS by a month misses the entire transitional senescence period. Therefore it is not recommended to use MODIS-LAI products to estimate the transition leaf-fall period.

6. Tables

	Season 2 (2008-2009)	**Season 3 (2009-2010)**
Early Successional Stage	0.79± 0.5	2.05± 1.9
Intermediate Successional Stage	1.2± 1	1.74± 1.5
Late Successional Stage	0.83± 0.6	1.81± 1.6

Table 1. Comparison of mean and standard deviation (SD) of *in situ* LAI values between season 2 (2008-2009) and season 3 (2009-2010) for early, intermediate and late successional stages. Higher SD in season 2 indicates increase in error propagation for *in situ* LAI values in all three successional stages.

	Temperature	**Soil Moisture**	**Humidity**
Early Successional Stage	P= $2E^{-5}$	P= $1.0E^{-41}$	P= $2.65E^{-9}$
Intermediate Successional Stage	P= $8E^{-4}$	P= $3.64E^{-1}$	P= $2.01E^{-7}$
Late Successional Stage	P= $3E^{-4}$	P= $1.50E^{-34}$	P= $2E^{-3}$

Table 2. Results of Kruskall-Wallis tests to determine the difference between climate readings for the 2008, 2009, 2010 dry seasons in the early, intermediate, and late successional stages. Results show that with the exception of soil moisture in the intermediate successional stage, all climate variables contained significant differences from one year to another.

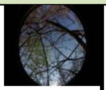
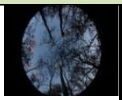
Early Successional Stage								
DOY	SOS			EOS			LOS	
	In situ	MODIS	HP	*In situ*	MODIS	HP	*In situ*	MODIS
2008-2009 Season 1	316	298		149	169		198	236
2009-2010 Season 2	290	289		134	161		209	237
Intermediate Successional Stage								
2008-2009 Season 1	277	281		167	161		255	245
2009-2010 Season 2	291	290		138	161		212	236
Late Successional Stage								
2008-2009 Season 1	320	290		167	161		212	236
2009-2010 Season 2	303	289		138	161		200	237

Table 3. Phenology projections of Start-of-season (SOS), End of Season (EOS) and LOS (Length of Season), for season 1 (2008-2009) and season 2 (2009-2010), using TIMESAT software.

7. Figures

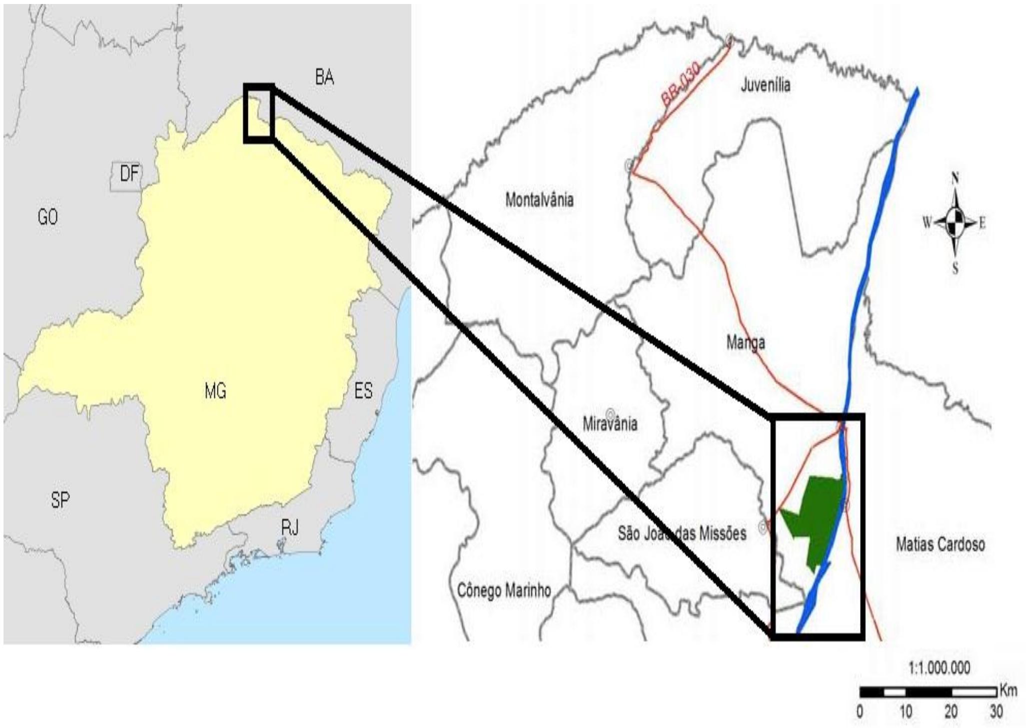


Figure 1. Boundaries of “Parque Estadual da Mata Seca (PEMS)” study site in Minas Gerais, Brazil (Modified from Belém, 2008).

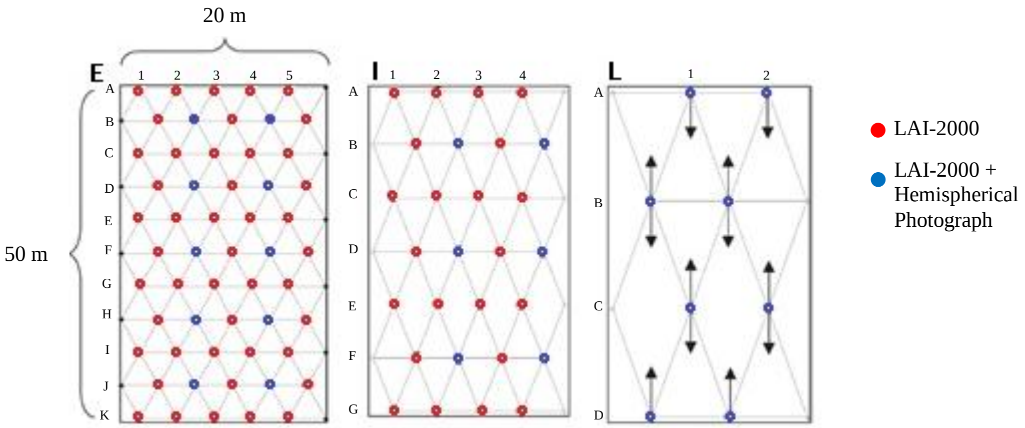


Figure 2. Example of LAI sampling scheme using the LAI-2000 for (E) Early (I) Intermediate (L) Late successional stage. Samples were taken at the apex of each triangle in both north and south facing directions. Red circles represent points sampled by LAI-2000 only, blue circles represent points sampled with LAI-2000 and Hemispherical Photographs (Modified from Nassar *et al.* 2008; Kalácska *et al.* 2005b).

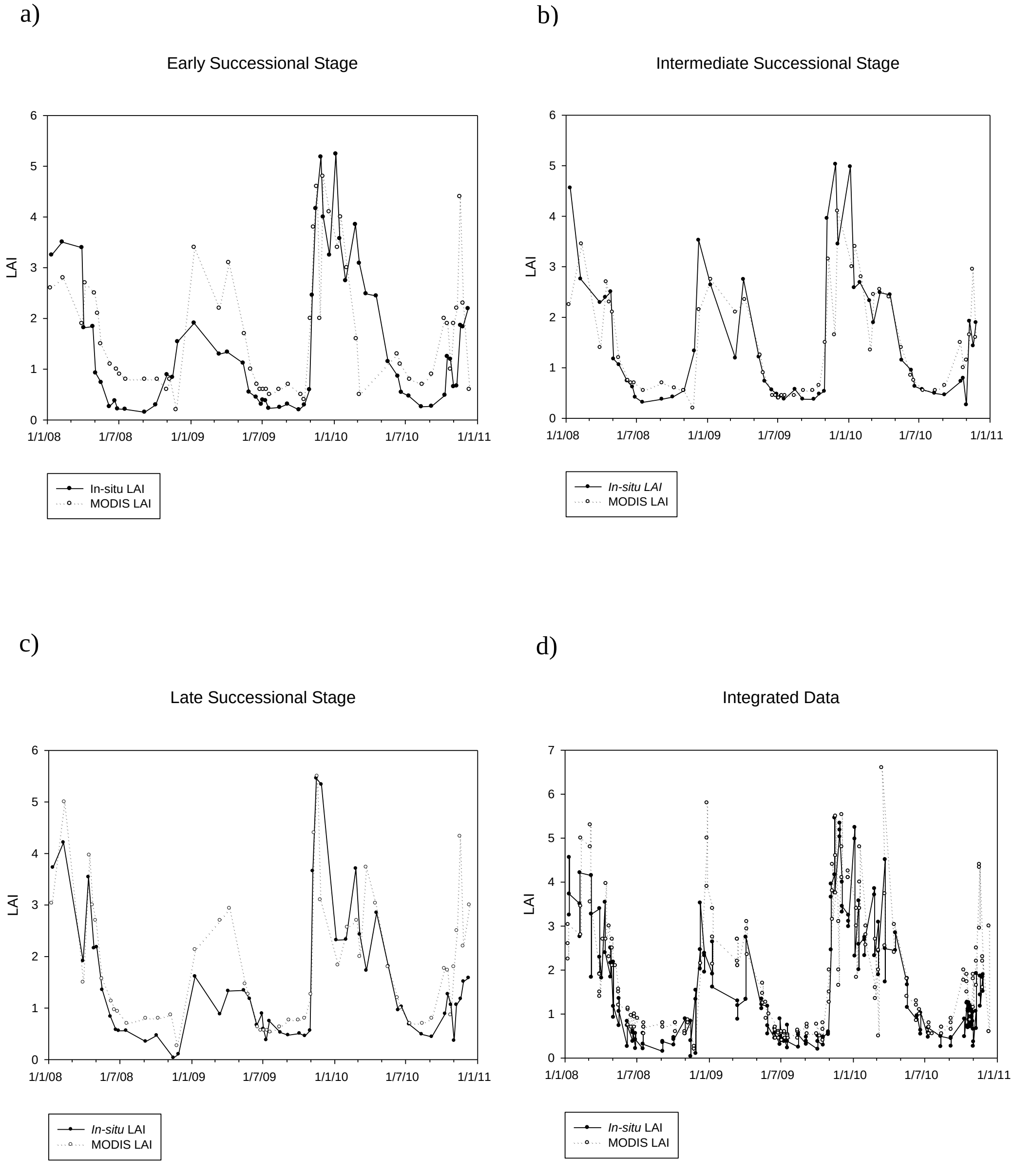


Figure 3. Time-series of *in situ* LAI data measured with the LICOR-2000 and MODIS-LAI products for the years 2008-2010: a) early, b) intermediate, c) late successional stages and d) integrated time-series values

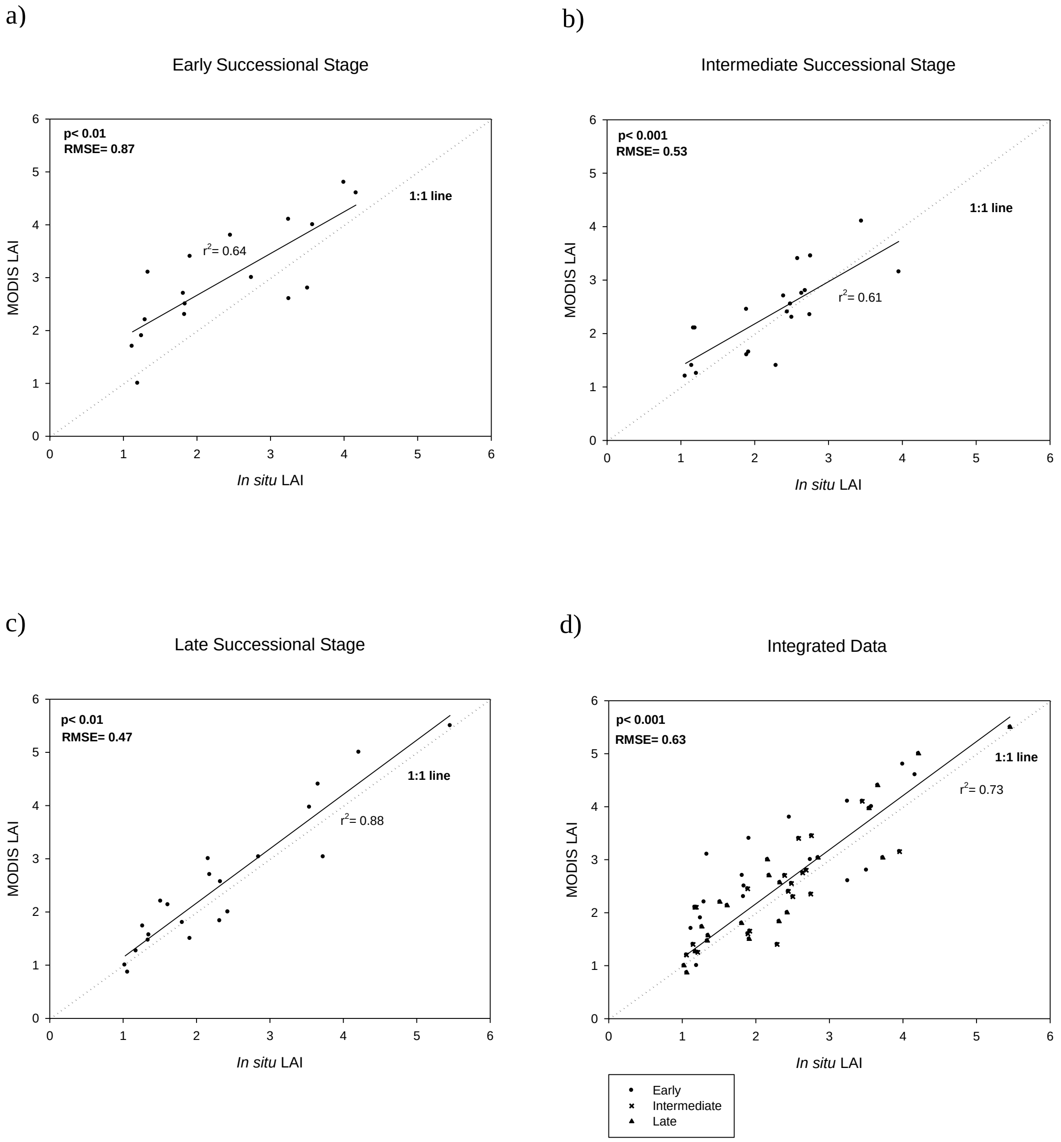


Figure 4. Comparison of *in situ* LAI data measured with LAI-2000 and MODIS-LAI products for the 2008-2010 growing seasons: a) early (P= 1.20E^{-4}; r^2= 0.64; RMSE= 0.87), b) intermediate (P= 4.7E^{-5}; r^2= 0.61; RMSE= 0.53), c) late successional stages (P= 2.86E^{-10}; r^2= 0.88; RMSE= 0.47) and d) integrated data comparisons (P= 1.75E^{-17}; r^2= 0.73; RMSE= 0.63).

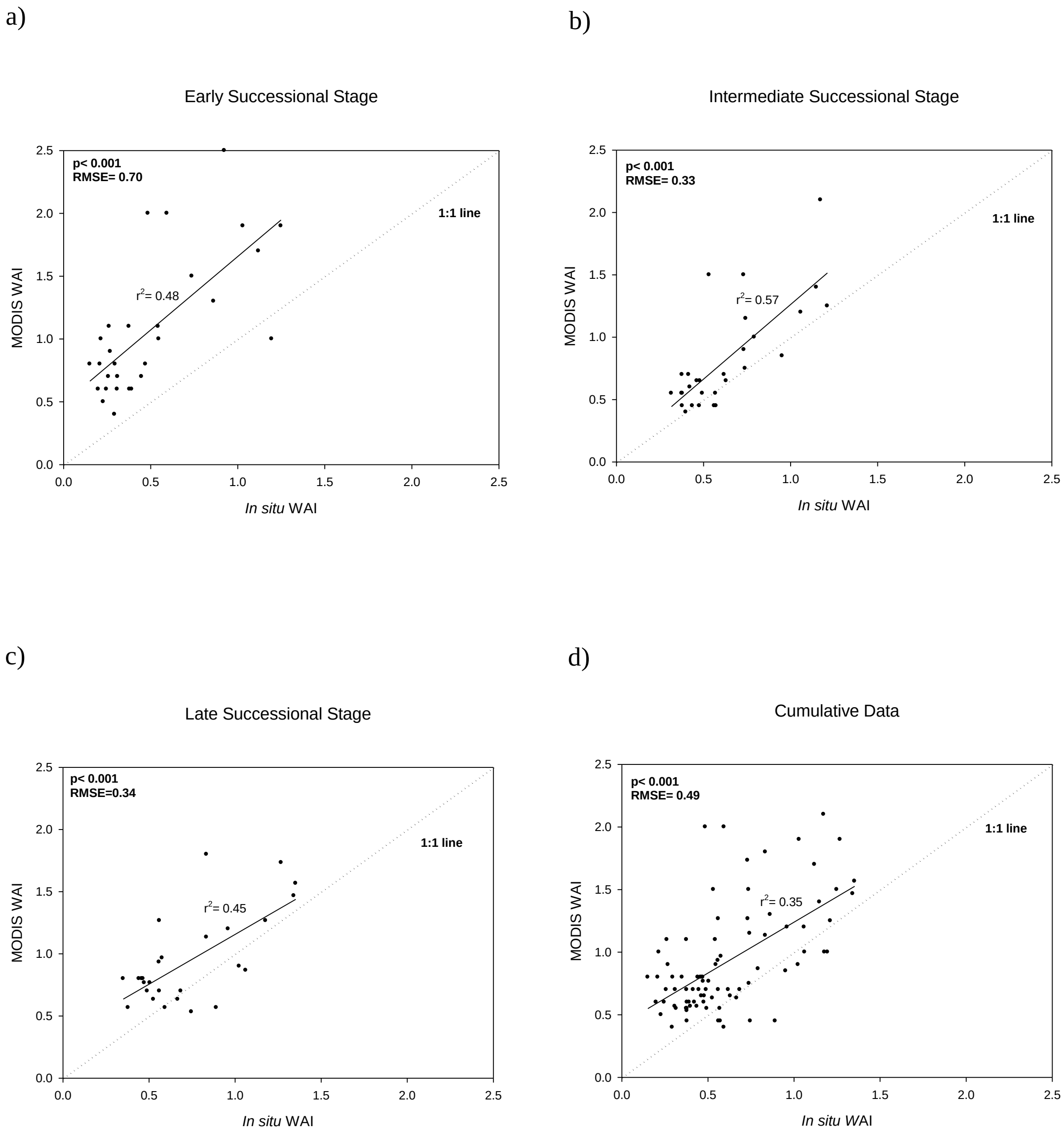


Figure 5. Comparison of *in situ* WAI measured with hemispherical photographs and MODIS-WAI products for the 2008, 2009 and 2010 dry seasons: a) early successional stage (P= 4.1E^{-5}; r^2= 0.48; RMSE= 0.70), b) intermediate successional stage (P= 2.16E^{-6}; r^2= 0.57; RMSE= 0.33), c) late successional stage (P= 1.42E^{-4}; r^2= 0.45; RMSE= 0.34) and d) integrated data (p= 7.67E^{-10}; r^2= 0.37; RMSE= 0.48).

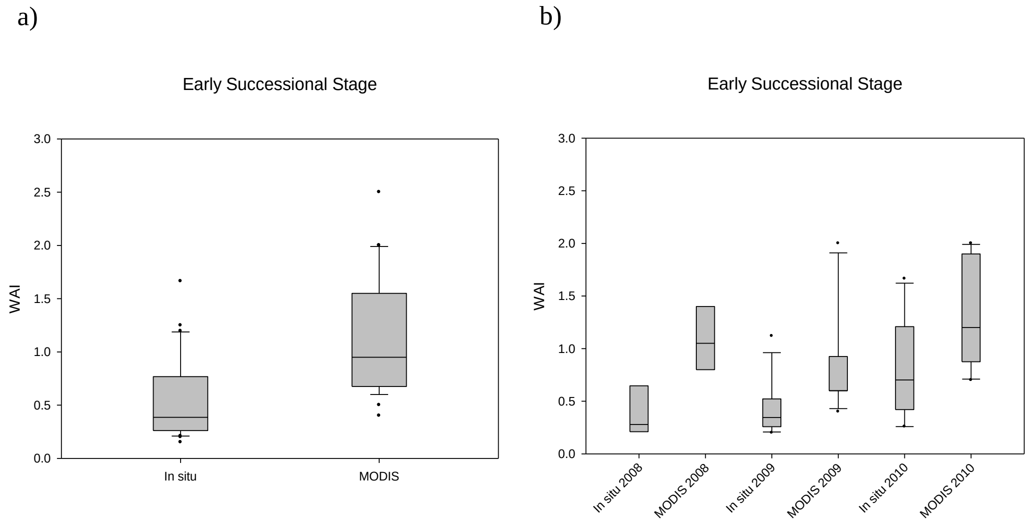


Figure 6. a) Data dispersal between *in situ* and MODIS-WAI products for the integrated dry seasons in the early successional stage showing significant differences between hemispherical photographs and MODIS measurements (H= 19.436, df= 1, P= 1E^{-6}). **b)** Data dispersal between *in situ* and MODIS-WAI products separated for the 2008, 2009 and 2010 dry seasons. Wilcoxon analysis shows significant differences between the *in situ* and MODIS-WAI products for each dry season (2008: H= 9.344, df= 1, P= 2E^{-2}; 2009: H= 10.93, df= 1, P= 9E^{-4}; 2010: H= 4.494, df= 1, P= 3E^{-2}).

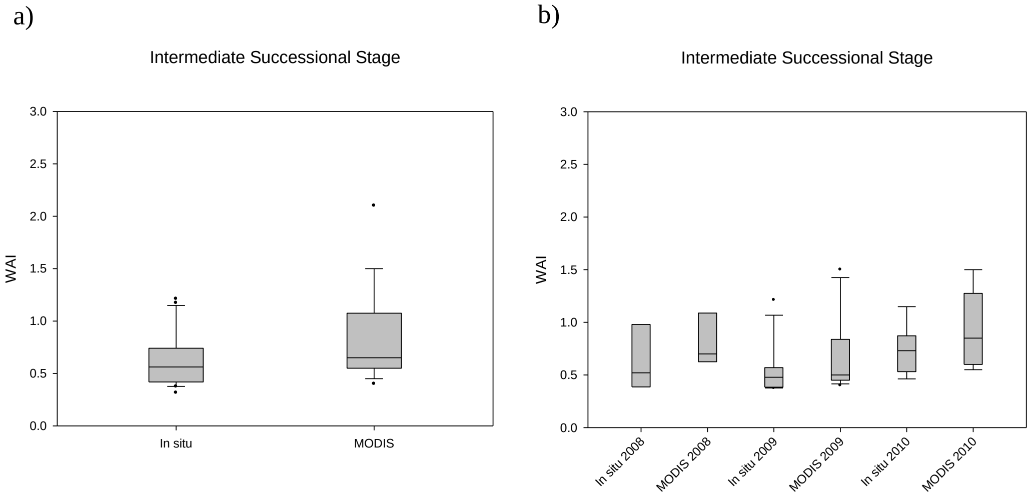


Figure 7. a) Data dispersal between *in situ* and MODIS-WAI products for the integrated dry seasons of the intermediate successional stage showing marginally significant differences between hemispherical photographs and MODIS (H= 3.937, df= 1, P= 4.8E^{-2}). **b)** Data dispersal between *in situ* and MODIS-WAI products separated for the 2008, 2009 and 2010 dry seasons. Wilcoxon analysis shows no significant difference between the *in situ* and MODIS-WAI products for each dry season (2008: H= 1.875, df= 1, P= 1.95E^{-1}; 2009: H= 1.09, df= 1, P= 3.10E^{-1}; 2010: H= 1.424, df= 1, P= 2.33E^{-1}).

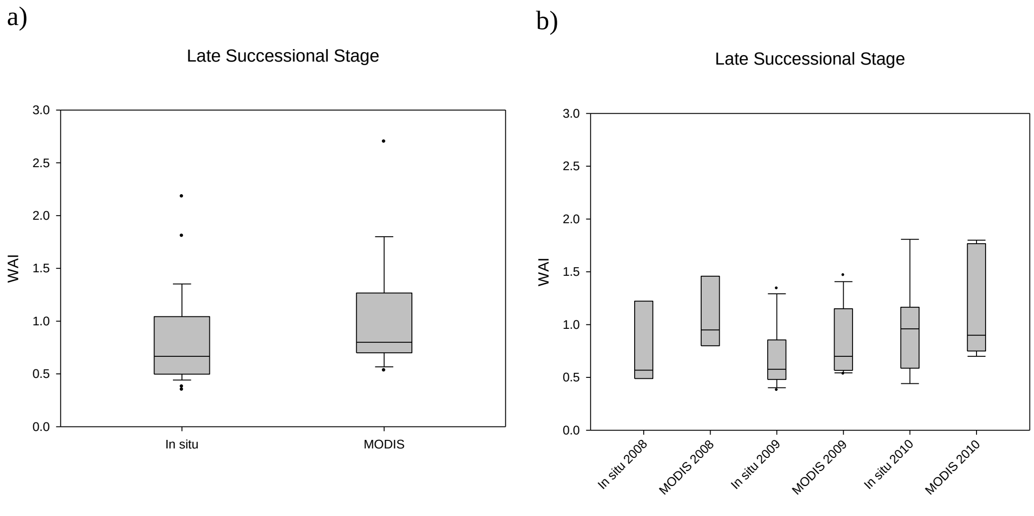


Figure 8. a) Data dispersal between *in situ* and MODIS-WAI products for the integrated dry seasons of the late successional stage showing significant differences between hemispherical photographs and MODIS (H= 4.846,df=1, P=2.8E^{-2}). **b)** Data dispersal between *in situ* and MODIS-WAI products separated for the 2008, 2009 and 2010 dry seasons. Wilcoxon analysis shows no significant difference between the *in situ* and MODIS-WAI products for each dry season (2008; H= 2.828, df= 1, P= 1.05E^{-1}; 2009: H= 2.26, df= 1, P= 1.40E^{-1}; 2010: H= 0.44, df= 1, P= 5.36E^{-1}).

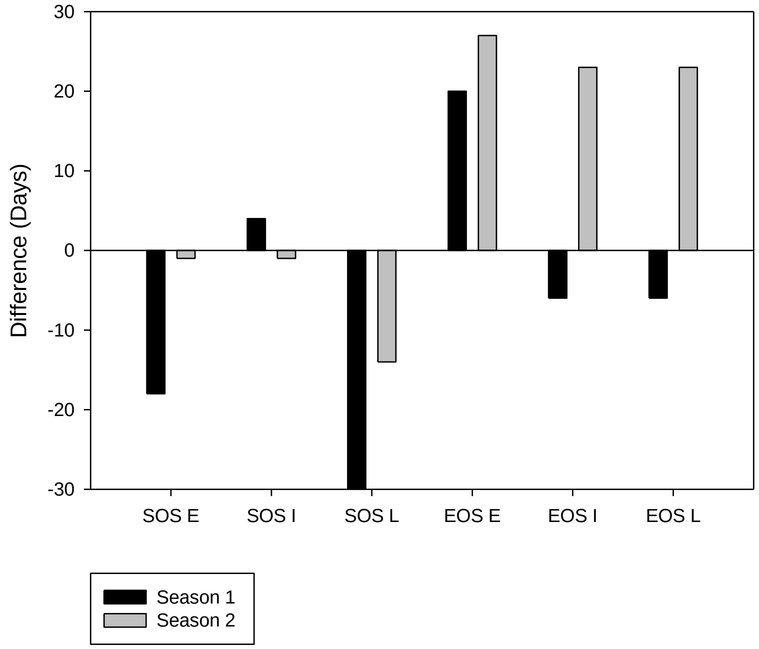

Differences in MODIS phenology estimates relative to *in situ* values per successional stage

Figure 9. Differences in the start-of-season (SOS) and end-of-season (EOS) for MODIS season 1 and season 2 estimates relative to *in situ* values for early (E), intermediate (I) and late (L) successional stages. Positive values indicate estimates were made after *in situ* data and negative values indicate estimates were made earlier than *in situ.*

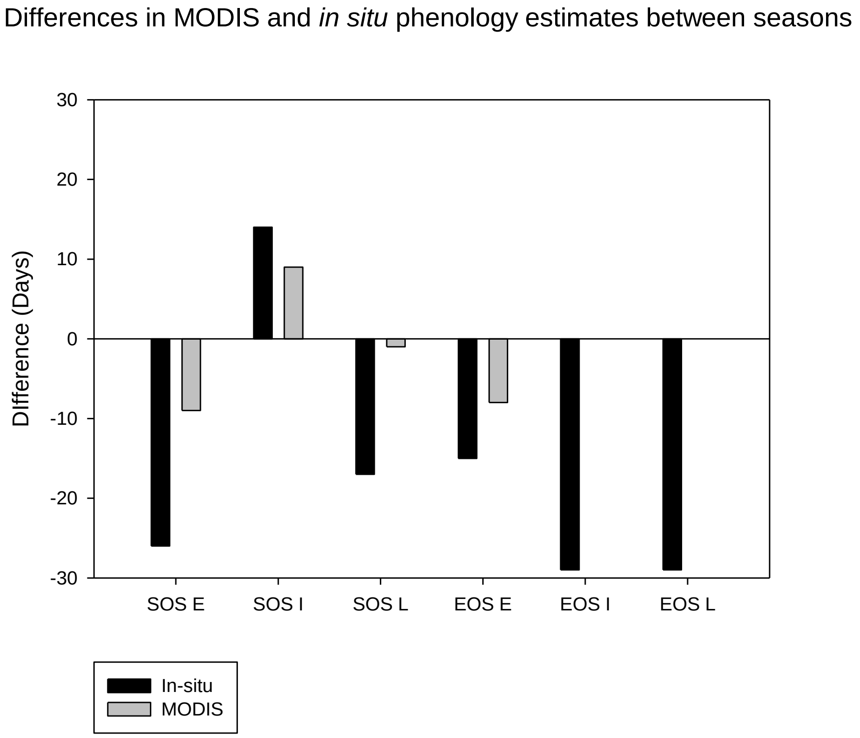


Figure 10. Differences in the start-of-season (SOS) and end-of-season (EOS) estimations between *in situ* and MODIS values for early (E), intermediate (I) and late (L) successional stages. Positive values indicate season 2 estimates were made after season 1, negative values indicate season 2 estimates were made before season 1.

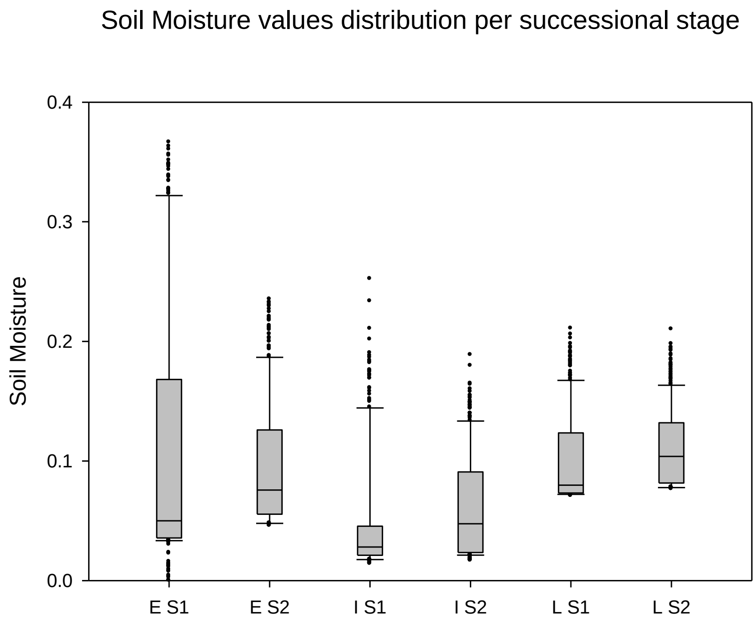


Figure 11. Box plots showing soil moisture distribution values between season 1 (S1: 2008-2009) and season 2 (S2 2009-2010) for the early (E), Intermediate (I) and Late (L) successional stages. Wilcoxon analysis results show significant differences in soil moisture values between season 1 and season 2 for all three successional stages (Early: H= 21.077, df= 1, P= $4.41E^{-6}$; Intermediate: H= 31.217, df= 1, P= $2.31E^{-8}$; Late: H= 57.195, df= 1, P= $3.95E^{-14}$).

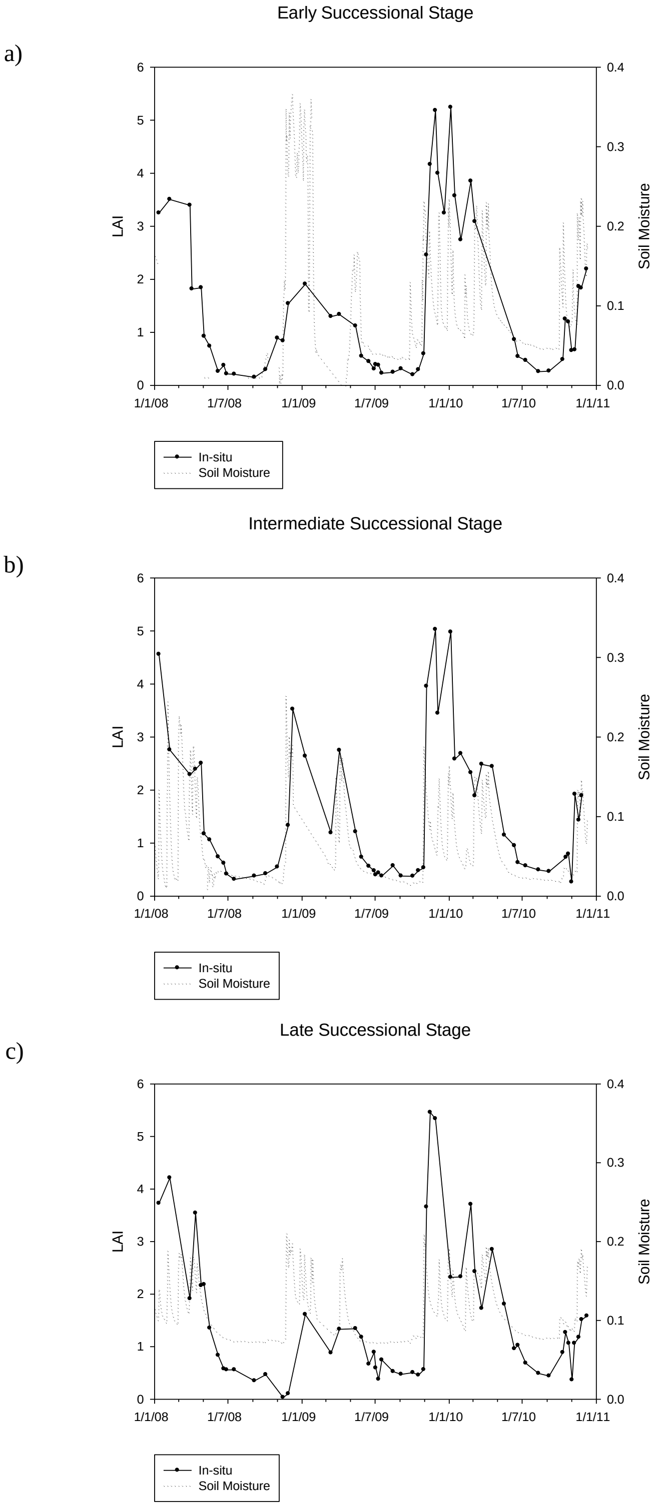


Figure 12. Time-series of *in situ* LAI values and soil moisture values measured with wireless sensor nodes for (a) early, (b) intermediate, (c) late successional stage.

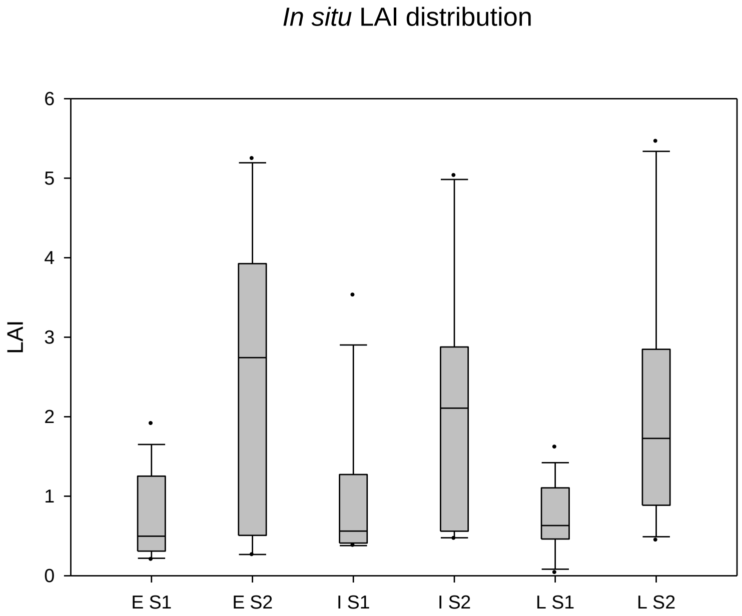


Figure 13. *In situ* LAI distribution of season 1 (S1) and season 2 (S2) for the early (E), intermediate (I), and late (L) successional stages. Wilcoxon analysis results show significant differences in LAI values between season 1 and season 2 for all three successional stages (Early: H= 6, df= 1, P= 1.4E^{-2}; Intermediate: H= 4.89, df= 1, P= 0.027; Late: H= 9.281, df= 1, P= 2.3E^{-3}).

1. CONCLUSION

This study proposed to answer the fundamental question as to how accurately MODIS-LAI products estimate Leaf Area Index and Woody Area Index and forest phenology in the tropical dry forest of Minas Gerais, Brazil in three different stages of succession.

1.1 Using MODIS-LAI products for estimation of Leaf Area Index in Tropical Dry Forests

The main finding in this study was that MODIS-LAI products' ability to estimate LAI accurately increases as successional stages increase. However, overestimation occurs at each successional stage and decreases as successional stage increases. The early successional stage had the highest amount of overestimation evidenced by the correlation relationship between *in situ* and MODIS-LAI; in contrast, the late successional stage had the highest correlation between MODIS-LAI and *in situ* LAI with minimal overestimation.

Firstly, scaling is a key factor affecting MODIS overestimation, with the LAI-2000 measuring at a scale of 50m and MODIS-LAI products measuring at a scale of 1km. Therefore, much larger areas are covered by the MODIS satellite that are not covered by *in situ* methods. Secondly, the viewing angle plays a key role, where nadir viewing MODIS-LAI products enable MODIS to capture not only the canopy but also understory leaf reflectance. Lastly, reflectance contributions from background elements augment reflectance values.

Overestimation has also been observed in other studies of broadleaf deciduous forests (Abuelgasim *et al.* 2006; Garrigues *et al.* 2008; Morisette *et al.* 2006), dryland forest (Sprintsin *et al.* 2009), and Kalahari woodland (Huemmrich *et al.* 2005). The fact that overestimation is consistent not only among the different successional stages in the

TDF, but also in other studies of different forest types indicates that this is a result of the MODIS-LAI products and future collections should provide better calibration of the LAI product output based on the inputs given in the algorithm.

However, since MODIS-LAI products in the late successional stage were estimated with relatively high accuracy, the results from this study could be applied to monitor LAI in the late stages of TDF's for a time lapse examination of phenological patterns. Wright and Muller-Landau (2006) suggest that secondary forests in the late successional stage resemble closely to old growth forests and can provide similar ecosystem services. Consequently, monitoring LAI in the late stage tropical dry forest would produce significant observations relating to the importance of conservation, ecosystem service production, contributions to curtailing habitat fragmentation, and the promotion of species conservation.

1.2 Using MODIS-WAI products for estimation Woody Area Index in Tropical Dry Forests

The first study of its kind, this section initiated out of conclusions presented in previous studies that areas of low LAI are more accurately measured by MODIS (Yang, 2006; Fensholt *et al*. 2004; Cohen *et al*. 2006; Morisette *et al.* 2006; Privette *et al*. 2002). It was therefore hypothesized, that because of this property, it was possible for MODIS-LAI products to measure WAI in tropical dry forests.

Regression analyses for each successional stage demonstrated that the intermediate successional stage showed the highest correlation between MODIS and *in situ* WAI values. The intermediate successional stage had the densest understory due to the presence of lianas and it is believed that the high density of woody material allowed for easier WAI detection by the MODIS satellite.

In addition, Wilcoxon analyses were used to evaluate *in situ* and MODIS WAI measurements for each season in all three successional stages. The analyses demonstrated that no significant differences exist between *in situ* WAI and MODIS-WAI estimates for each season in the intermediate and late successional stage. This indicates that MODIS-LAI products have the-potential to measure WAI in broadleaf dry successional forests where woody area density is high. This study should be replicated in other TDF areas in order to corroborate the results.

Using MODIS-LAI products for estimating WAI would permit researchers to estimate forest wood density in a much faster, convenient and cost-efficient manner than through *in situ* hemispherical photographs. In addition, the Wilcoxon analyses results indicate that WAI index values can be compared between seasons to obtain information about forest loss or regeneration such as tree mortality. Lastly, by using WAI as a measure of forest understory density the presence of lianas within a forest could be detected.

1.3 Using MODIS-LAI products to estimate phenology of tropical dry forests

By using TIMESAT to compare the seasonal parameters of *in situ* values to MODIS-LAI products (Jönsson and Eklundh 2002, 2004), the study demonstrates that MODIS detects SOS 1-2 weeks before *in situ* values (Table3, Fig. 9). A possible explanation could be due to the canopy producing leaf flush later than understory vegetation; MODIS is able to capture understory leafing which leads to identifying forest greening before *in situ* values (Table 3, Fig. 9).

In addition, MODIS SOS estimations between seasons are within 9 days of one another, which is in contrast to *in situ* SOS estimations which differ from season1 to season 2 at a range of 2-3.5 weeks. This large variation in the estimations of *in situ* values between seasons could be due to climatic factors. The high synchronicity between soil moisture and *in situ* LAI time-series indicates that soil moisture had a great effect on *in* *situ* canopy phenology patterns which may not have affected MODIS phenology as drastically due to differences in scale.

Conversely, the *in situ* LAI time-series estimates EOS before MODIS. The differences in estimates between the *in situ* values and MODIS are large and could also be attributed to the scaling factor of MODIS versus the *in situ* values. For the TIMESAT software program to detect EOS, it requires a reduction threshold to 10% of the amplitude of the seasonality curve, a value frequently used by Jönsson and Eklundh (2002, 2004). However, because of the large amount of vegetation contained within a MODIS pixel, the time required for LAI reduction to this value is delayed. Since the threshold value is set arbitrarily, the study could be improved by determining SOS and EOS using different threshold values and correlating these estimates to *in situ* SOS and EOS estimates. The threshold value which produces the most accurate correlation would be selected.

Understory effects also play a role in the delayed detection of EOS. Intermediate and late stages of the forest contain lianas that have deeper root systems than the surrounding trees and because satellites are able to detect understory liana phenology, it is likely that the canopy-detecting LAI-2000 detects EOS before MODIS plot measurements.

In addition, the time-series for both the intermediate and late stage show a significant increase in LAI as well as a significant increase in SM from season 1 (2008-2009) to season 2 (2009-2010) both of which show that there was an increase in leaf production between the two seasons. Consequently, because of the scale at which the satellite views the canopy, the MODIS satellite may require more time to detect leaf loss especially at higher leaf densities.

Therefore, because MODIS-LAI seasonality identifies the beginning of the growing season before *in situ* values in all successional stages; MODIS-LAI products would be useful for predicting the beginning of the growing season in tropical dry forests for any successional stage. However, early successional stage SOS estimates need to be viewed cautiously as the heterogeneity of species composition and background light reflectance results in early estimations of up to one-month. Early and Intermediate stages are able to estimate within an accuracy of roughly 2 weeks.

In contrast, EOS estimates would not be beneficial to conduct as MODIS-LAI products overestimate EOS by approximately 20 days for the intermediate and late stage, and 30 days for the early successional stage. Clearly, the overestimation of EOS by a month misses the entire transitional senescence period. Therefore it is not recommended to use MODIS-LAI products to estimate the transition leaf-fall period.

1.4 Concluding Remarks

The results from this study help to provide further insight on the ability of MODIS satellite products to provide information about secondary tropical dry forests. Firstly, the 8-day MODIS-LAI products enable the long-term monitoring of old growth secondary tropical forests, providing information about its biological productivity that can be used to estimate forest cover, habitat availability and ecosystem services. Secondly, the capability of MODIS to detect WAI values aids in the identification of intermediate from early successional stages in tropical dry forests and provides information about forest dynamics such as tree regeneration and mortality. This information is important for determining habitat availability in secondary forests for primary forest species. Lastly, by estimating SOS, MODIS-LAI products aid in determining the resources available for primary or secondary forest species during the leaf growing season.

By providing a more efficient way to gather information, MODIS-LAI products can contribute to the discussion of whether secondary forests play an important role in habitat conservation, providing ecosystem services and mitigating forest cover and biodiversity loss at a time where forest area is decreasing at a faster pace to meet human consumption demands.

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