Monitoring Seasonal and Secondary Succession Processes in Deciduous Forests using Near-Surface Optical Remote Sensing and Wireless Sensor Networks

by

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ABSTRACT

The goal of this thesis is to address the need for improved monitoring of forest ecosystem dynamics in the context of anthropogenic global change by proposing the use of near-surface optical remote sensing approaches paired with emerging wireless sensor network (WSN) technologies in order to evaluate changing forest seasonality and succession patterns, specifically in the semi-arid tropics and sub-tropics. Climate change is expected to affect terrestrial ecosystems through bottom-up control of primary productivity by extending or decreasing growing season length in seasonally photosynthetic vegetation. Human land use imposes top-down control over ecosystems by modifying disturbance regimes, with subsequent ecosystem regeneration depending on land use policy and management. The interplay between bottom-up climate forces and top-down anthropogenic forces on tropical dry forest (TDF) ecosystem recovery and productivity is poorly understood and is an underlying theme in this thesis. As such, this thesis introduces and assesses the novel application of WSN technology for spatio-temporal micrometeorological characterization and near-surface optical remote sensing of deciduous broadleaf forest canopy photosynthetic dynamics. The results reveal major benefits as well as challenges in the synergistic use of optical in-situ and satellite observation platforms for monitoring leaf phenology and secondary succession processes in deciduous forests, with case studies from the boreal and tropical dry broadleaf forests.

Chapter one reviews the motivations behind the methods and experiments presented in this thesis. Chapter two reveals how low-power wireless data transmission is influenced by seasonal changes in boreal forest leaf phenology and weather conditions to help improve WSN designs for forestry applications. Chapter three describes local meteorological drivers of leaf phenology in detail for a

Brazilian TDF in the state of Minas Gerais, and further explores how sub-canopy climate moderation effects are influenced by secondary forest stand age and extreme drought seasonality in order to characterize TDF microclimatic ecosystem services and better understand drought risk factors for seedling establishment and tree recruitment in future TDFs. Chapter four investigates the correlations between remotely sensed and near-surface hyper-temporal observations of TDF phenology in the context of future change detection for climate driven shifts in TDF productivity, revealing significant limitations in MODIS vegetation greenness time series for phenology monitoring in TDFs. Finally, chapter five reviews the significance and main contributions of these experiments. The experimental results presented here may be specific to tropical dry and boreal forest ecosystems, but the methods and ideas apply to all forest ecosystems in order to improve environmental monitoring technologies and our understanding of vegetation seasonality and secondary forest succession in our rapidly changing global environment.

PREFACE

Some of the research conducted for this thesis forms part of an international research collaboration called Tropi-Dry, led by Professor G.A. Sanchez-Azofeifa at the University of Alberta, with Professor M. M. Espirito Santo being the lead collaborator at the University of Montes Claros. The specific wireless sensor network technology referred to in chapter 2 and 3 was conceived by Dr. G.A. Sanchez-Azofeifa and co-designed and manufactured by OlsoNet® Communications and Lord-Microstrain Systems®, with the assistance of Mr. Doug Calvert of Hoskins Scientific ® and myself.

Chapter 2 of this thesis has been published as *Rankine, C.J., Sanchez-Azofeifa, G.A., MacGregor, M.H. 2014. Seasonal wireless sensor network link performance in boreal forest phenology monitoring. IEEE Proceedings of the Eleventh Annual International Conference on Sensing, Communication, and Networking, Singapore*. I was responsible for the experimental design, data collection and analysis as well as the manuscript composition. The co-authors contributed to the results interpretation and final manuscript edits. The data analysis and results interpretation in chapter 2, 3, and 4 are my original work.

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TABLE OF CONTENTS

CHAPTER 4 - COMPARING MODIS AND HYPERTEMPORAL NEAR-SURFACE VEGETATION INDICES FOR MONITORING TROPICAL DRY FOREST PHENOLOGY ALONG A SUCCESSIONAL GRADIENT……………………………………………….…90

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Background and Study Motivation

The story of human global expansion is very much related to the story of human use of forests and their resources. The world over, forests offer a multitude of valuable natural resources for humanity, from direct goods such as food, fuel, fibre, and medicine to indirect services like biodiversity reservoirs, air and water purification, carbon sequestration and climate moderation (Chazdon 2008; Hungate and Hampton 2012; Pearce 1996; Pimentel et al. 1997; Smith 2003). Globally, forests contain 80% of all plant biomass, are responsible for three quarters of terrestrial photosynthesis, and store more carbon than is currently found in the Earth's atmosphere (Pan et al. 2013). Of the nearly four billion remaining hectares of forests covering one third of the land area worldwide, 36% are primary, 7% are replanted, and 57% are secondary forests that have naturally regenerated after disturbances (FAO 2010). Currently, nearly half of all forested lands - roughly 1.6 billion ha - have a management plan, with conservation areas being primarily designated for soil, water, and biodiversity protection purposes (FAO 2010). While over a billion people in rural communities around the world depend on forests for their livelihood, currently less than 15% of forests are formally protected by law, leaving the vast majority vulnerable to unsustainable management and deforestation practices (Schmitt et al. 2009).

The United Nations Food and Agriculture Organization's Global Forest Resource Assessment maintains inventories of global forest statistics and trends as part of their efforts to reduce global food insecurity through improved land resources management. The relationship between land use, land cover change, and food production goes hand in hand with the sustainable management of forests. As human populations grow and urban areas expand, deforestation rates increase and forest management practices need to evolve to keep up to these rapid environmental changes. From 1990 to 2015 satellite observations reveal a global net loss of 129 million ha of forest, corresponding to a 17.4 Gt decrease in forest carbon stocks, equivalent to 6% of the global total (FAO 2015). The 2010 FAO reported an average net loss of 5.2 million ha yr-1 of forest from 2000 to 2010, down from 8.3 million ha yr-1 from 1990 to 2000, indicating rates of global deforestation are decreasing but still remain unsustainably high.

The tropics have experienced the greatest deforestation rates in the late 20th and early 21st centuries. Tropical forests contain the largest above-ground carbon stocks and highest species richness and diversity of any terrestrial ecosystem, making them key biomes in the global carbon cycle and vital biodiversity reservoirs (Erwin 1988; Pan et al. 2013). Several of the largest deforestation fronts are in South America (FAO 2015), where changes in global market demands and land use policy have driven most of the recent land conversion (Grau and Aide 2008). Socioeconomic policies tend to change more frequently in developing nations (Santos-Paulino 2012), and as land use drivers change or farmland becomes unproductive from overuse, abandoned deforested land may naturally regenerate into secondary forests. This has been occurring at large scales across the Neotropical landscape for several decades (Rudel et al. 2010). In the tropics and subtropics, secondary forest growth can occur quickly and act as significant carbon sinks which have proven challenging to accurately quantify on regional and local scales (Foody et al. 1996; Defries et al. 2002; Olschewski and Benitez 2005). The diversity and complexity of natural forest regeneration processes, coupled with variable land-use history effects, has created large uncertainties in our ability to predict tropical reforestation rates and estimate potential limitations to carbon sequestration and ecosystem service resilience, particularly in a changing global climate (Barbosa et al. 2014).

Changes in global climate stability can stress forest ecosystems by altering precipitation patterns, increasing temperatures, and modifying the frequency and intensity of weather extremes (Allen et al, 2010; Williams et al. 2013). Tropical tree mortality rates due to drought and forest fires are expected to increase significantly in the 21st century (Anderegg et al. 2013; Allen et al. 2010). Similarly, excessive deforestation in the tropics can alter local precipitation patterns by weakening the momentum between land-atmosphere heat and moisture exchanges, which can affect forest regeneration capacities, especially in the semi-arid tropics (Charney 1977; Laurence and Williamson 2001; Laurence 2004). Aide et al. (2012) estimated from moderate resolution satellite observations that in Latin America more than 36 million ha of land regained woody vegetation cover between the year 2001 and 2010, nearly half of that in Brazil alone, yet very little is known about the biometeorology of secondary tropical forests in relation to successional processes.

Tropical dry forest (TDF) biomes comprise over 40% of tropical forests and are under significantly greater threat from deforestation and climate change than tropical wet and moist forests (Portillo-Quintero and Sanchez-Azofeifa 2010; Sanchez-Azofeifa et al. 2005). In the Neotropics, TDFs are the preferred biome for agricultural land conversion due to their ideal climate and soil characteristics for growing crops and thus experience high rates of fragmentation from human disturbances. Unfortunately, research on TDF ecosystems is systematically underrepresented in comparison to tropical moist forests, therefore secondary TDF succession and climate resilience is poorly understood (Blackie et al. 2014). With an unprecedented amount of young forests undergoing rapid secondary succession processes in the Neotropics, forest managers and researchers now more than ever require tools to efficiently manage forest landscapes and better understand natural regeneration processes for sustainable forestry practices and dynamic carbon stock assessment in an increasingly global context.

Given the enormous amount and diversity of environmental data being generated in the 21st century, forest researchers, managers, and policy makers require advanced information technologies to track how ecosystems respond to human disturbances and recover after intensive land use or resource extraction. Proficient local and regional environmental management demands continuously up to date information on ecosystem health and functionality. Satellite remote sensing techniques have become an increasingly powerful tool in mapping forest extent, structure, and long-term dynamics (FAO 2015; Pan et al. 2013). However, space-based observations still suffer from atmospheric interference that limit data availability, require extensive ground validation work and complex image post-processing methods (Lu 2006; Malenovsky et al. 2009; Barbosa et al. 2014), and therefore do not offer near real-time information sources. Remotely sensed data offer ideal spatial resolution for large-scale forest monitoring but typically lack sufficient temporal resolution to capture important, but highly dynamic, forest ecosystem processes (Barbosa et al. 2014). Unseasonal weather, disease and pest infestations, drought stress, or more subtle changes in sub-annual forest productivity are not readily captured via most satellite sensor observations. Such dynamic and short-lived processes can significantly affect ecosystem productivity, and are expected to increase in frequency and severity with accelerated climate change, but are often not observed in enough detail to adequately quantify their effects on forest ecosystem services (Parmesan et al. 2000). Furthermore, changes in seasonal forest productivity caused by extended or reduced growing season lengths are good indicators of important but poorly understood climate-biosphere interactions. Such processes require high temporal frequency observations in order to detect significant long term trends in shifting seasonality (Visser and Both 2005). Enhanced monitoring of semi-arid tropical forests in particular will enable a greater understanding of dryland desertification processes and improve Global Dynamic Vegetation Models, which rely on empirically derived model constraints as critical inputs to our understanding of Earth's climate and ecosystem resilience to change.

In-situ wireless sensor networks (WSN) are an underutilized technology in ecology and Earth sciences with the potential to overcome some of the major challenges in forest ecophysiology monitoring and ecosystem assessment efforts. The key advantages of WSNs are continuous, objective, and automated data acquisition of rapid environmental processes in remote locations with poor accessibility (Porter et al. 2005; Rundel et al. 2009). Small, spatially distributed environmental sensor arrays equipped with low-power radio communication are capable of monitoring forest biophysical parameters simultaneously over large areas and delivering the data in near-real time. WSNs can typically be quickly deployed, collect large amounts of spatially and temporally explicit data, and are often more cost-effective than larger, long-term data logging systems that are not designed to be used in large arrays. These advantages of using WSNs make them ideal tools for in-situ comparisons of forest dynamics with moderate resolution satellite observations for spatio-temporal validation of vegetation remote sensing products. Optical light sensors can be used to detect plant photosynthetic dynamics and phenology in deciduous forests by measuring canopy reflected and transmitted sunlight patterns with far greater certainty than space-based surface reflectance measurements (Wilson and Meyers, 2007). Doing this with large sensor arrays increases the reliability of data collection and accuracy of derived data products, but is cost-prohibitive with traditional data logging systems. WSN research and development is primarily a computer science domain and has been focussed largely on the indoor and urban environments, therefore WSNs are not well-suited for long-term, off-the-grid, outdoor operation (Corke et al. 2010). Despite the many advantages wireless environmental sensor systems offer over traditional manual in-situ forest monitoring, there are few WSNs designed for forest applications and many challenges and questions exist regarding their practical use in forest science.

SPECIFIC HYPOTHESES AND STUDY OBJECTIVES

In light of the previously discussed literature and current state of knowledge, this body of work explores the use of environmental WSNs for hyper-temporal near-surface optical sensing of forest phenology and succession characterization in boreal and tropical forests, and addresses some of the current uncertainties and limitations of this newly accessible technology for forest research and management. In this context, this thesis evaluates three specific hypotheses:

a. The application of wireless sensor networks for forest ecology and remote sensing validation will be limited by the communication link performance of the WSN. The local wireless communication success will be dependent on the vegetation structure, being modified both by the spatial and temporal dynamics of the vegetation and weather conditions.

b. Wireless sensor networks will improve our understanding of spatio-temporal dynamics in forest understory microclimates by enabling synchronized observations of high frequency temporally dependent spatial variations in below-canopy micrometeorological variables.

c. The high temporal resolution of near-surface remote sensing of radiometric fluxes above deciduous forest canopies provides significant advantages over satellite remote sensing for monitoring canopy phenology, and is a viable approach to moderate resolution satellite validation, at the expense of reduced spatial sampling.

Goals and Objectives:

a. To evaluate the signal strength variations across a 2.4GHz wireless sensor network in a Canadian boreal forest as a function of canopy phenology and meteorological conditions.

b. To understand the micrometeorological drivers of vegetation phenology in a Brazilian Tropical Dry Forest and use wireless sensor networks to characterize understory microclimatic succession during TDF regeneration.

c. Assess the climate canopy moderation capacity of a secondary tropical dry forest as a function of stand age.

d. To evaluate TDF phenology seasonality parameters obtained from moderate resolution remote sensing product (MODIS NDVI/EVI) using near-surface canopy radiometric sensor networks in-situ.

CHAPTER SYNOPSES

Chapter Two, *Seasonal Link Performance of a Wireless Sensor Network in Boreal Forest Phenology Monitoring*, explores the effects of seasonal changes in meteorological variables and the forest leaf area dynamics on wireless sensor network radio signal strength in a boreal Aspen forest stand in northern Alberta, Canada. Low power wireless communications for sensor networks is well characterized in theory, simulations, and controlled indoor testing environments, but little is known about how deciduous vegetation and weather conditions can limit network connectivity in real world forest settings. I reveal new patterns in 2.4 GHz signal strength variability with forest phenology and air temperature using robust regression and discuss the implications of the results for network design and operation in forestry applications. I also demonstrate the first known long-term boreal forest environmental sensor network with near real-time phenology monitoring capabilities. This work has been published in the Proceedings of the 2014 Eleventh Annual IEEE International Conference on Sensing, Communication, and Networking (SECON).

Chapter Three, *Seasonality and Succession and of a Brazilian Tropical Dry Forest: Phenology and Climate Moderation in Secondary Stands*, examines the correlations and time-lags between tropical dry forest phenology and local meteorological conditions as well as the difference in canopy phenology between young and old secondary TDF stands using near-surface optical remote sensing in Brazil. Empirical data on meteorological drivers of tropical dry forest phenology is required to understand how TDFs may respond to changing climate patterns. In addition, patterns of understory microclimate variability between rainy and dry seasons and successional stands are revealed using wireless sensor networks, and canopy moderation capacity of temperature and moisture extremes is related to forest stand age and structure. The importance of microclimate succession with secondary TDF canopy structural regeneration is discussed in the context of climate change and TDF ecosystem resilience for sustainable land management in the semi-arid Neotropics. This chapter was submitted as a research manuscript to the Journal of Agriculture and Forest Meteorology in October 2015 and is under peer review.

Chapter Four, *Evaluating MODIS Vegetation Indices for Monitoring Tropical Dry Forest Phenology across a Successional Gradient using Optical Phenology Towers*, reviews the current issues with remote sensing of tropical dry forest phenology in the context of photosynthetic growing season change detection in the dry tropics, and promotes the use of near-surface optical remote sensing as a low-cost synergistic approach to land surface phenology monitoring. Correlations are investigated between several years of canopy tower-based vegetation greenness index trends and the MODerate resolution Imaging Spectroradiometer (MODIS) satellite vegetation indices for several TDF plots across different aged secondary stands in southeastern Brazil. Furthermore, using phenometric analysis of growing season parameters I identify key discrepancies between the MODIS and in-situ derived start and end of season dates using varied temporal aggregation windows, showing temporal disagreements on the order of days to weeks for TDF phenology trends depending on the observation platform selected. The results indicate a need for ongoing validation efforts for satellite based monitoring of forest seasonality and subsequent productivity patterns in the dry tropics. This chapter was submitted as a research manuscript to the Journal of Remote Sensing of Environment on July 2015 and was accepted for peer review.

LIMITATIONS TO RESEARCH PROJECTS

As the majority of the data used in this thesis is time series observations, either high frequency short term or aggregated long term measurements, there is limitations in what analyses could be performed due to data availability. Using electronic data loggers in forest environments results in frequent data collection interruptions and data loss due to persistently high humidity, wildlife interference, and power supply failures. In addition, the wireless sensor network technology used in these studies were custom developed for this research and thus is considered bleeding-edge technology as it is not well user-hardened or performance perfected, and thus is subject to greater failure rates than commercially available hardware. Not all intended pairwise comparisons between sites or sensors could be performed due to the inaccuracies introduced when relating non-synchronized observations of spatially variably phenomenon. To determine spatial differences between meteorological data the measurements must be synchronized to minimize any introduced bias of transient phenomenon. Similarly, not all inter-annual comparisons within sites could be performed due to sensor or logger failures. Since the study sites are very remote and challenging or expensive to access, not all equipment failures could be readily attended to, and the resulting analyses were selected based on the available data. Data availability for the complete time series used can be reviewed via the University of Alberta's Enviro-Net® Cyber-Database.

The study sites used for these investigations were selected as they were part of the University of Alberta's Center for Earth Observation Science ecological remote sensing ground-truthing research network and provided the necessary research infrastructure for long-term field campaigns. While all studies include the use of sensor networks, the analysis performed for chapter two was chosen for a boreal forest rather than a tropical dry forest as it is the only study site equipped with a wireless sensor network that records radio signal strength indicators, necessary for assessing network communication patterns. Ideally, the network communication analysis would have also been performed in a tropical dry forest site but the radio strength measurement instrumentation was not developed at the time of the Brazilian field campaigns. Furthermore, the wireless sensor nodes could only be deployed within communication range of the data aggregators. This signal distance limitation is a major driver of network topology designing for sample plots, and therefore sampling design is largely dictated by trying to cover the largest forest area, within signal range, with the least number of sensors required to represent the variable being continuously measured. While these miniaturized WSNs are significantly less expensive than using many stand-alone data loggers, there were still limitations to how many sensor locations could be continuously sampled within a network for a given study plot due to the cost prohibitive reality of deploying and maintaining large sensor networks.

While components of this research aim to improve methods for detecting shifts in deciduous forest productivity induced by climate change, it should be noted that a much longer term in-situ study would be required to distinguish long-term trends in vegetation phenology from the natural variability observed between growing season years. A more in depth review of study limitations are discussed within each chapter.

Final Opening Remarks

The following chapters in this thesis aim to highlight the application of sensor networks and optical remote sensing for high temporal resolution observations of deciduous forest biophysical dynamics. Using emerging information and communication technology for novel research applications has the potential to significantly advance our knowledge of forest ecological processes and greatly improve our ability to foresee threats to ecosystem services due to increasing global environmental stress. This dissertation explores old domains of forest science with tools that provide fresh insights, and pushes new frontiers in ecological monitoring and remote sensing of the environment.

This research was carried out as part of the University of Alberta's Center for Earth Observation Science environmental Wireless Sensor Network development project, Enviro-Net®, and as part of the TROPI-DRY international collaborative research network designed to improve our understanding of and ability to conserve Neotropical Dry Forests.

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CHAPTER 2

SEASONAL WIRELESS SENSOR NETWORK LINK PERFORMANCE IN BOREAL FOREST PHENOLOGY MONITORING

ABSTRACT

While indoor wireless sensor network (WSN) research has recently flourished for monitoring civil and industrial infrastructure, considerably less attention has been given to the development of reliable outdoor WSNs capable of long-term operation in challenging remote locations. I present wireless sensor network link performance results from the first year of monitoring micro-meteorological conditions alongside the 802.15.4 link received signal strength indicator (RSSI) within an old growth stand of deciduous boreal Aspen forest (*Populus tremuloides*) in Northern Alberta, Canada. Thirty-six weather proof nodes were equipped with meteorological sensors and distributed across one hectare in the forest understory to assess the application of WSNs for observing high resolution changes in seasonal ecosystem productivity and forest phenology.

We describe here the density distribution of node RSSI using Gaussian kernel density estimates in relation to node antenna-receiver orientation and vegetation seasonality. RSSI across the network displays a lognormal distribution with an increasing bimodal tendency with path length through the forest stand. Spatial variability in RSSI is discussed with respect to forest structure. A strong temporal relationship between RSSI variability and plant canopy development is observed with a 20 dBm or 100 fold difference in mean network radio signal strength from spring leaf presence to fall leaf absence. The meteorological and biophysical factors associated with this trend are explored using multiple regression and relative factor importance analysis. Our results indicate that in addition to meteorological data, spectral vegetation density metrics are useful in assisting deployment planning and network performance diagnostics when using wireless sensor networks for remote forestry applications. The longevity and performance of this outdoor WSN can be seen as a new standard for harsh network-climate tolerance in northern boreal environments.

INTRODUCTION

Ecosystem carbon sequestration, water storage and purification, and biodiversity tend to be greatest in forested landscapes due to higher primary productivity rates and habitat diversity (Costanza et al. 1997). As such, a higher ecosystem service value is associated with forests than most other terrestrial land cover classes. The Canadian boreal forest is the largest biome in North America covering nearly six million km^2 and 58% of Canada's land area (Carlson et al. 2009). An estimated 208 billion metric tonnes of carbon are stored in the Canadian boreal (Carlson et al. 2009), more than 25 years worth of current global greenhouse gas emissions. As the climate in northern latitudes changes, there have been detectable shifts in growing season lengths (Zeng et al. 2011) with little certainty in how these shifts in plant phenology influence net ecosystem exchange and carbon balances in the vast boreal forests.

Like all plant communities, the primary productivity of northern ecosystems is strongly regulated by weather conditions. Meteorological and micro-meteorological dynamics can be challenging to observe in remote locations due to accessibility, power, and communication limitations. While global remote sensing systems provide us with meteorological and forest productivity information these data come at coarse spatial and temporal resolution. For high temporal resolution of boreal forest micro-meteorological variables and remote sensing ecosystem productivity validation I employ wireless sensor networks (WSNs) for distributed area monitoring of canopy-absorbed photosynthetic active radiation (APAR), air temperature, relative humidity, soil moisture, and the normalized difference vegetation index (NDVI) based on dual broadband light sensors.

Boreal forest ecosystems present challenging radio environments for the implementation of wireless sensor networks, both in design and operation. In this environment, radio signal excess path loss is difficult to predict due to the complexity and seasonal dynamics of canopy structure, woody area, and weather conditions. These factors also make the long-term network performance uncertain. Here I report on one year of operation of a 2.4 GHz wireless network (802.15.4) in a Canadian boreal forest setting, and examine the relationship between several logged network and environmental metrics:

a) 802.15.4 link received signal strength indicator (RSSI) and node-receiver spatial orientation

b) Temporal variations in RSSI with seasonal evolution of forest canopy biophysical structure as a function of leaf phenology

c) Temporal variations in RSSI with daily mean air temperature, vapor pressure, solar insolation, and wind speed during different seasonal growth phases of the forest.

RELATED WORK

Radio Propagation Through Vegetation

Radio signal attenuation is unavoidable due to free-space path loss, and is further mediated by signal reflection, refraction, diffraction, and absorption during wave propagation. Besides the fixed parameters of antenna-receiver specifications radio frequency (RF) transmissions in outdoor settings are influenced by local topography, terrain contours, weather, and the properties of path interception materials. The effects of vegetation on RF propagation have been widely investigated for telecommunications but not as extensively for ad hoc wireless sensor networks (ITU-R 2010; Jia et al. 2010). Typical empirical studies measure excess path loss beyond what is expected given transmitter-receiver parameters to indicate vegetation signal fade (ITU-R 2010; Savage et al. 2003). Attenuation due to vegetation interference has been demonstrated for frequencies between 30 MHz and 60 GHz, with evidence of more pronounced fade at frequencies above 1 GHz as wavelengths become smaller than plant structures (ITU-R 2010).

Depending on plant canopy height and antenna-receiver orientation there is potential for several main signal transmission routes including ground reflection, surface-wave propagation over the top of plant canopies, and through scatter/diffraction around leaves, branches and tree trunks (ITU-R 2010; Savage et al. 2003). Modelling this path loss generically has proved difficult due to the diversity of vegetation architecture. Forests structure can be particularly complex having varying contributions of foliar and woody densities paired with the heterogeneous distributions of vertical and horizontal forest strata.

Network RSSI: While WSNs are not typically equipped with network analyzers to measure radio frequency response or absolute power both 802.11 and 802.15.4 RF physical layers do provide received signal strength (RSSI). This can be converted to a signal power indicator in dBm through network specific parameters; however this means that there is no standardized RSSI metric used in WSNs. Although RSSI is a useful network communication diagnostic tool it has not been demonstrated as an accurate predictor of absolute node distance or position in a WSN (Benki et al. 2009; Parameswaran et al. 2009).

Forest Applications of WSNs

While there has been a significant increase in wireless sensor network research in the last few years, the majority of studies deal with simulated networks (Kolega et al. 2011). An increasing number of applied outdoor WSNs are being studied but very few of these deployments can be considered long-term and typically report testing operations on the scale of days to weeks (Ceriotti et al. 2010; Luo et al. 2011; Jiang et al. 2010). Uses for WSNs in forest monitoring are plentiful and have been observed already for forest fire detection (Zhang et al. 2008), stream flow (Simoni et al. 2011), snow and soil moisture (Kerkez et al. 2012), and microclimate monitoring (Press 2011). To our knowledge no other WSN system exists for tracking forest phenology and none of the reported networks operate far from an urban center. Due to the ease of human access, reliable power source, and network gateway connectivity, urban forest and parkland settings have been the traditional testing grounds for long-term real-time wireless sensor networks. Our study moves to a more challenging testing grounds of an extremely remote setting where access is restricted for 4-6 winter months and the old growth forest retains undisturbed natural features.

Outdoor Wireless and Weather

The effects of weather conditions on wireless communications have garnered the attention of radio physicists and cellular communication companies since the mid-20th century. Such studies report that only high temperatures (>25°C) cause significant degradation of radio signals (ITU-R 2010). This temperature dependent signal quality was recently described for an outdoor deployed WSN by Wennerstrom et al. (2013). Although the cause of this temperature dependent behavior is unclear it is often considered to be due to antenna mechanics or electronic hardware limitations at higher temperatures (Boano et al. 2010).

Precipitation does tend to produce intermittent signal fading as well but these are typically short-term interference events and are more pronounced at higher frequencies (Savage et al. 2003; Paul et al. 2011). Interestingly the influence of water vapor on 2.4 GHz sensor network communication is still not well understood; some reports indicate no effect of humidity levels while others have observed minor correlations (Ceriotti et al. 2010; Luo et al. 2011). It is likely that these mixed results originate from the diversity of methods used to measure such a response. For such reasons, as discussed by Wennerstrom et al. (2013), water vapour pressure rather than relative humidity is used as an air moisture metric for RSSI-humidity comparisons. Finally, wind movement through vegetation has been observed to increase the variance of received radio signal strength due to the changes in multi-path propagation as trees sway in the wind. Hashim and Stavrou (2006) and Cheffena and Ekman (2009) showed that high wind speeds produced radio signal fading of 1.8GHz through 60GHz radio frequencies due to stochastic Rician interference.

Motivation: I am not aware of any other examples of WSNs being applied to forest phenology monitoring nor has there been any demonstration of stable long-term operation of WSNs in remote old-growth forest settings. I believe this is the first study to explore the use of WSNs in vegetation that quantifies the effect of plant canopy development and senescence on radio network communication.

EXPERIMENTAL OVERVIEW

While the implementation of this remote wireless sensor network was primarily motivated by investigation of boreal forest primary productivity, phenology, micro-meteorological monitoring, and remote sensing validation, this analysis of network performance is essential for continued progress in optimized planning of forest WSN deployments.

Study Site

The monitoring instrumentation is located within the joint industry-research forestry district for Ecosystem Management Emulating Natural Disturbance (EMEND) for large-scale variable retention boreal forest harvest experimentation in northwestern Alberta, Canada (Figure 2-1). Regional climate is characterized as humid continental. Mean annual temperature of the nearest long-term weather station 85km SE is 1.2°C (min/max recorded extremes = -49/37°C) with a mean annual precipitation of 400mm and mean snow depth of 12cm (Environment Canada 2014). The study plot, located at 56.74 lat. -118.35 long and 870m elevation, is situated in an old-growth stand of Trembling Aspen (*Populus tremuloides*) with a broad leaf deciduous canopy (Figure 2-1). There are two generally distinct vertical layers of vegetation, the understory from the ground up to 4m height and the overstory canopy at 15-20m with an observed decreasing woody density with height. A 30m tall carbon flux monitoring tower was constructed just outside the forest in a clearing and used as the base station for centralized data aggregation. Our monitoring initiative began in mid-summer of 2012 and is on-going.

Sensor Network Deployment

Our wireless sensor system was co-developed at the University of Alberta's Center for Earth Observation Sciences via Hoskin's Scientific and Lord-Microstrain Sensing Systems partnerships. This system has evolved from six years of real-world long-term testing of wireless sensor networks in forest environments (Sanchez-Azofeifa et al. 2011). The network operates on the ISM 2.4 GHz radio band. Radiated power is programmable from 0 dBm (1 mW) to 20 dBm (40 mW) for extended range communication with a bi-directional RF link using IEEE 802.15.4 data packet delivery architecture. Nodes use a 2.5 dBi gain omnidirectional antenna with linear polarization. Circuitry is encased in weather proof, pressure dynamic enclosures rated at IP X7. Received signal strength indicator (RSSI) is reported in dBm, which uses a log-scale with a practical maximum RSSI around -20 dBm and complete data packet loss below -90 dBm.

Thirty-six nodes were mounted at 1m height in a hexagonal or honeycomb topology (20 m sides) over a plot of roughly one ha of forest adjacent to the instrumentation tower (Figure 2-2). Nodes were positioned with their antennas vertical and on the receiver side of the post to minimize interference (Figure 2-3). Each node has a digital temperature and relative humidity sensor placed in a solar radiation shield and upward facing hemispherical photosynthetic active radiation (PAR) sensor (Apogee SQ-110). Several nodes were further instrumented with soil moisture probes measuring volumetric water content. Tower nodes were equipped with both PAR sensors and pyranometers (Apogee SP-110) for monitoring above canopy incident and reflected radiation used to derive a broadband NDVI (Wilson and Meyers 2007). The entire network samples with sub-second clock synchronization and was configured for five minute sampling during the growing season and thirty minute sampling for the winter.

Real-Time Data Retrieval

Sensor data is aggregated at a single base station equipped with an outdoor omnidirectional 8 dBi high gain transceiver antenna positioned at 20m height on the tower outside the forest. The antenna is angled at twenty degrees from vertical to direct the main radio signal lobe towards the middle of the network; this orientation demonstrated a significant increase in mean network RSSI upon deployment. Since this remote site is completely off the wired power and communication grid, internet access was obtained using a cellular GSM modem with a 14 dBi gain directional Yagi antenna pointed at the nearest cellular tower which was located 48 km away. This enables bi-directional communication whereby, in addition to remote sensor data retrieval, node sampling and sensor configurations commands can be remotely uploaded to the network.

Aggregator node power is maintained by a very large battery bank (200 Ahr) and a 75 Watt solar panel in order to sustain operation during the cold winters with minimal solar recharge potential. Furthermore, an innovative power timer system was implemented to only turn the aggregator system on several times a day to collect back-logged data from the network, transmit to the nearby GSM uplink, then shut down to conserve power. Sensor data is also logged in the two megabyte memory of each node. Whenever a connection to the receiver is established the one thousand most recent data entries are forwarded to the aggregator node in order to back-fill any previous lapses in data transfer. Data is uploaded to a cloud storage server and forwarded to our laboratory database servers at the University of Alberta at each received data sampling interval. Data can then be retrieved and visualized on demand in the Enviro-Net® web portal in near-real time. For more information on this cyber-infrastructure see Pastorello et al. (2011).

ANALYSES AND OBSERVATIONS

Winter Resilience: Many of the nodes in the network were removed in the fall of 2012 but fifteen nodes were left in place unattended for six months during the harsh winter from November 2012 to April 2013 to test endurance. Batteries were found depleted for three of the nodes but the surviving twelve nodes collected a complete annual data set including the full phenological cycle of the forest. These twelve nodes are the focus of our long-term RSSI analysis. The location of these nodes is shown by grey circles in Figure 2-2. They are organized into four rows each 20 m further into the forest from the receiver tower. Each row has three columns referred to as left (L), center (C), and right (R) facing the network from the receiver, hereafter referred to by row number (r1-r4) and column location.

The raw temperature and PAR data from node r1C in Figure 2-4 shows detailed diurnal and seasonal trends for both variables for the full 12 month cycle. As expected, seasonal temperatures lag behind solar radiation levels. Winter temperatures drop below -20°C without any data loss due to node failures. The variability between micro-meteorological observations for different sensor nodes is not discussed here.

Temporal Patterns in RSSI

The daily mean network RSSI (µRSSI) was between -64 and -68 dBm prior to the leaf flush in May and showed a general decrease with canopy development throughout May and June. A single node located in the nearest row actually had a significantly higher RSSI than the rest of the network for the duration of the forest green-up. It then demonstrated a sudden decrease in RSSI and afterwards conformed to the communication pattern of the rest of the network. µRSSI ranged between -70 and -75 dBm for the majority of the growing season with a gradual increase as the summer progressed (Figure 2-6). A drastic increase in network RSSI from -70 to -63 dBm occurred between October 8 and 11. This sharp transition is not well understood but did correspond to a strong drop in air temperature and high-speed wind gusts. It is possible that the inclement weather induced a rapid leaf drop event in the senescent canopy resulting in increased signal transmission. While the NDVI data does not reflect this pattern, the leave had likely already lost their pigment prior to leaf abscission. From then on the network RSSI increased steadily towards a mean of -55 dBm. Given the logarithmic scale of RSSI this represents a nearly 100-fold difference in signal power reception between the spring minimum and the fall maximum RSSI.

Density Distributions: RSSI and micro-meteorological (micromet) sensor data from April 21 to November 30 2013 was further aggregated to hourly and daily means and variances for each of the understory nodes. The observations over this 220-day period amounted to 50,000 individual points per sensor, for a total of three million stored entries across the sensor network.

As seen in Figure 2-5, the greenness trend from the tower NDVI nodes indicates that the growing season began in the first week of May and ended in early November. For the analysis, in addition to looking at RSSI trends across the whole season, the RSSI and micromet data were further grouped by forest growth phases, or phenophase, into five periods based on NDVI: spring dormancy, spring green-up, canopy maturity, fall brown-down, and fall dormancy. This was done in order to see if the relationships between the biophysical and meteorological variables and network RSSI differed throughout the season.

RSSI sample density distributions were created using a guassian kernel with a bandwidth equal to the twice the sample standard deviation to smooth out minor peaks. Details of this method can be found in the CRAN project density function in the base stats package (R Project 2008). Distribution moments are described for both temporal subsets of the mean network RSSI as well as spatial RSSI subsets from individual nodes. Separating the network average RSSI into forest vegetation phenophases reveals a shifting signal density distribution throughout the growing season (Figure 2-7). A strongly platykurtic distribution is seen for the spring dormancy, green-up, and canopy maturity phenophases with increasing kurtosis and decreasing mean RSSI for these sub-sampled periods. The fall senescence, or brown-down, displays a highly bi-modal RSSI tendency reflecting the sharp transition from low to high RSSI in October. The leafless fall dormancy period also has a bimodality in network RSSI but with a shift towards a higher RSSI than during canopy senescence. The phenophases selected based on canopy greenness do have representatively distinct radio signal distributions in the spring and summer but the fall brown-down period does not. This is likely due to the fact that a decreasing NDVI in the fall indicates a loss of leaf pigments but not always a dropping of leaves. As such, I expect the forest fPAR to correlate better with fall RSSI since it better reflects changes in canopy structure.

Spatial Patterns in RSSI

Given our power transmission and reception parameters, I expected an optimal theoretical RSSI of -61 dBm at 40m and -69.5 dBm at 100 m distance between the nodes and base station receiver due solely to free space path loss. Nodes in the first row positioned 40 m from the receiver report a significantly lower mean RSSI around -68 dBm indicating excess path loss in the environment. However, at 100 m distance the nodes in the furthest row from the base station, row 4, report a mean RSSI around -70 dBm revealing almost no excess path loss. One possible explanation for this comes from examining the receiver-node orientation in Figure 2-8. The peak radiation lobe of the tower antenna is directed more towards the back of the network. Alternatively, the apparent two layer vertical structure of the forest may promote horizontal transmission of radio signals while dampening vertical radio propagation. Further work needs to be done in characterizing such an effect as the interaction between forest structural layers and radio propagation could prove important for implementing WSNs over larger distances within forested landscapes.

The tendency towards a bimodal distribution is more prominent in the more distant nodes than in the nodes closer to the receiver (Figure 2-9). It might be presumed that the more distant nodes have more intermittent connections with occasional strong packet delivery resulting in such a distribution. However, as shown in the temporal density histograms, this bimodal distribution was an apparent effect of seasonal transition into the fall monitoring period. With those considerations, it is also relevant to further discuss here the environmental factors in the forest – both biophysical and meteorological - capable of inducing seasonal changes in network signal strength.

Network RSSI Predictors

Regression Analysis: The investigation into which forest environmental predictor explained the greatest amount of temporal variability in daily mean RSSI and signal strength variance was based on four different multiple linear regression model assessment approaches. These describe the relative importance of each variable, or regressor, in the model using different criteria of contribution to the coefficient of determination (R^2). The *first* method for relative importance is most straightforward and simply indicates the direct independent contribution of individual regressors' R^2 to the model with no adjustment for interactions among regressors. Then the *last* approach looks at additive effects of each regressor indicating how much each additional variable adds to the model and is also referred to as usefulness. Next, the *Pratt* method (Pratt 1987) for relative importance assessment takes an innovative but somewhat controversial approach by standardizing the model coefficients so they are scale-invariant for comparison. This method can be less intuitive to interpret as it can produce negative coefficient contributions. Finally, I use the *LMG* method for averaging over ordering which is arguably the most robust regression technique as it uses both direct and adjusted effects of model regressors for more effective decomposition of R^2. Averaging over ordering circumvents the sequential ordering bias of regressors in the model for situations where the order of added regressors influences the model results. Furthermore, I bootstrap each method to clearly differentiate between similar regressor importance's using a replicate size of 1000 to produce 95% confidence intervals for each regressor importance metric. This analysis was performed using the *relaimpo* package in R statistical software (Gromping 2006).

Six environmental variables were included in the multiple regression, four meteorological and two canopy state parameters. Meteorological variables included in the model were daily mean air temperature (T), vapor pressure deficit (VPD) calculated from temperature and relative humidity (Paw method, 1987), wind speed (WND) and down-welling solar radiation (SR) from the meteorological station located on the tower positioned just above the WSN base station. Forest canopy metrics included in the regression analysis were the normalized difference vegetation index (NDVI) and the fraction of absorbed photo-synthetically active radiation (fAPAR). Both of these variables were measured using the optical sensor capabilities of our WSN and are the most commonly used remote sensing phenology indices to indirectly measure canopy leaf area and density (Wilson and Meyers 2007). Variables were added to the regression analysis in the following sequence:

$$GLM = \mu RSSI \sim fPAR + NDVI + T + VPD + SR + WND$$

Results: Greatest agreement between the relative importance methods was found between the *LMG* and *first* approaches. The *last* and *Pratt* method resulted in much larger confidence intervals and thus did not help as much in differentiating variable contributions to the model. The output from all four methods are still shown here in order to assess agreements between them, but the *LGM* is discussed in most detail as it is considered the most robust regression approach.

Across the entire 220-day monitoring period from April through November the regression showed that 68% of the total variability in daily µRSSI can be explained by these six regressors ($p<0.001$). All four methods of post-analysis for revealing predictor relative importance reported that NDVI contributed to the majority of this coefficient and was generally a strong predictor of signal strength for the network (Figure 2-10). Air temperature ended up being the second strongest contributor to mean signal strength next to NDVI. Together NDVI and temperature compose over 60% of the model fit (Table 2-1).

Breaking the regression into three broader sub-season phenophases, the 50 day spring green-up (May-June), the 70 day stable mature canopy (July-Aug), and the 80 day fall senescence (Sept-Nov) revealed different regressor coefficients for the linear fit (Table 2-1). The sub-seasonal model with the largest overall coefficient of determination was found to be during the green-up phenophase with 88% of the variability in RSSI during May and June explained by the model. The most important radio signal predictor here again was the NDVI, with temperature and fAPAR as equally important second place contributions. All three variables considered together made up nearly 90% of the model fit. Changes in mean RSSI were explained to a lesser degree by the regression during canopy maturity and senescence phenophases with 54% and 52% of the variability accounted for, respectively. To a large extent temperature was the best predictor of signal strength while the canopy was mature in the summer time but during the fall senescence it was not as strong a predictor as compared to NDVI (Figure 2-11).

In terms of daily signal variance, all four importance methods agreed that temperature was the strongest regressor when looking at the whole season (Figure 2-10). While vapor pressure deficit appeared to cause the most variance in daily RSSI during the green-up period and temperature was the most likely cause for signal variance during the spring and fall dormancy, it was found that wind speed was by far the strongest predictor of signal variance for the duration of the mature canopy growth phase (Table 2-1). Although wind speed made up 74% of the model fit for signal variance, the regression still only explained 18% of the mature canopy RSSI variance.

While solar radiation explained a significant proportion of the RSSI during the fall and wind was a good predictor of increasing signal variance during the peak of the growing season, these parameters could arguably be dropped from the linear model to increase simplicity. Running the regression for the whole growing season with just temperature and NDVI only decreased the R^2 from 0.68 (SE ±1.9 dBm) to 0.63 (SE ±2.0 dBm). The standard error of the NDVI + temperature linear model increased from 2.0 dBm to 2.3dBm when NDVI or temperature was the only regressor.

DISCUSSION

Spatio-Temporal Signal Strength

We have shown that the distribution of RSSI will differ depending on the temporal subset of measurements in a seasonal forest environment. Assessment of network communication based on RSSI will need to take all growth phases of a deciduous forest into consideration. Given the lognormal tendency of the signal strength distribution across the whole growing season I recommend the use of the median value over the mean for describing and comparing RSSI data from individual nodes. Node location did not show large differences between the peaks of highest density in the RSSI distribution curve but rather the shape of the tail often revealed spatial differentiation of signal patterns (Figure 2-9). The shape of the density distribution tail may be a good indication of how network link performance changed specifically for each node during the seasonal changes in leaf area.

Recommendation 1: Scouting environmental WSN deployments during different vegetation growth periods is necessary to understand how network communication will change seasonally. If data can be stored locally at the sensor node or at relay nodes and is not required in real-time then deploying sensors nodes during leaf-off can achieve greater distance communication. In this case data can be bulk off-loaded to the base station annually when leaf-off radio connection resumes. Furthermore, I recommend at least one node in an outdoor WSN be equipped with light sensors for simple vegetation density monitoring in order to supplement network performance diagnostics.

Forested Radio Environments

In the regression analysis I looked at forest environmental factors controlling absolute signal strength as well as signal strength variability. Weather conditions are highly dynamic in outdoor environments, and even more so at high latitudes. Sensor network hardware has to cope with powerful diurnal temperature fluctuations, often in the range of 20°C and upwards of 60°C on an annual basis. Material expansion and contraction as well as electrical resistance with temperature change will undoubtedly affect circuit and antenna performance in permanent outdoor wireless communications systems. The data indicated a large effect of temperature on signal variability in our boreal phenology WSN, but no single mechanism for this can easily be identified. It may also be possible that strong thermal air gradients near the ground surface during hot summer days could potentially refract radio waves and interfere with wireless signals (as is seen with visible light near hot surfaces), but no work on this has been described to our knowledge.

In accordance with Hashim and Stavrou (2006) and Cheffna and Ekman (2009) wind speed was found to increase the variability of received signal strength across the network. Luo et al (2011) discussed their findings of 'bursty' links, or range-edge nodes with intermittent communication in a forest setting, but could not offer an explanation of this sporadic connectivity. I propose that such bursty links are a result of vegetation swaying in wind gusts. There was no direct correlation found between the vapor pressure of the air and the received signal behavior. Perhaps this was due to the humidity sensor being located on the tower above the canopy where humidity levels are typically lower than in the forest understory where the nodes are located. No investigation was done into the influence of rainfall events on the network links but it was observed that our two-way remote network communication capabilities are severely degraded during and shortly after rainstorms. In addition, precipitation was more frequent during the spring and early summer months than later in the summer and fall, which could explain the general increase in mean signal strength across the duration of the mature canopy phenophase.

The observed relationship between in-situ NDVI and RSSI is likely not due to excess absorption of signal as my literature review indicates that longer radio waves are not strongly attenuated by leaf matter alone over short distances (Savage et al. 2003). It is more likely that the signal pathway is modified through reflective and diffractive scattering by leaves. These results do not present an explicit model of seasonal RSSI behavior in forests as this relationship is expected to be highly site specific. Further work needs to be done examining the leaf angle distribution and vertical structure of forest environments in order to derive a more broadly applicable model of WSN radio link performance in forest settings.

Recommendation 2: I have learned from past experiences that deploying WSNs when leaves are not present will often result in the seasonal loss of network connectivity. For year-round communication a network should be deployed just after the peak of the green-up when signal loss is greatest. I also suggest that deployments at forest sites with high average wind speed conditions could take advantage of the connectivity burst opportunities created by wind-induced tree movements. This would require the ability to back log data at the sensor or relay node for opportunistic data transmission, a network feature that has proven quite valuable for WSNs in forestry. For more advanced aggregator power management, a base station equipped with a suite of meteorological sensors could be optimized to broadcast data collection commands only when optimal conditions exist such as when lower temperatures and strong sustained winds are detected.

Further Work – Not discussed here is the influence of snow on signal strength. Many of our nodes were partially or completely buried under snow during the winter and still continued transmitting data but no analysis of RSSI was performed with snow depth because our primary concern was with respect to the growing season signal dynamics. To better assess the effect of air humidity on the network communication a comparison of relative humidity, dew point, absolute humidity, and vapor pressure deficit should be conducted to help clarify and standardize the water load and state variables for RF communication interference. Similarly, a standardized design for radio transmitter and receiver orientation would benefit translation of these results to other studies. As it stands currently, this innovative boreal monitoring wireless test bed is set to continue operating for several more years, after which more network performance analysis will be reported including power management, hardware and software progression, and optimized network design.

Conclusions: Meteorological conditions and seasonal dynamics of plant communities must be considered when planning an outdoor deployment of a WSN. It was demonstrated that the previously unexplored use of in-situ spectral vegetation indices proved useful in explaining the strong seasonal variability in network link performance. Provided long-range RF communications are spatially and temporally non-uniform in forest settings, large area environmental monitoring may best be achieved by multi-hop routing protocols in wireless sensor networks. Despite the challenges associated with operating long-term outdoor WSNs, forested landscapes are ripe with ecosystem services and in-situ wireless sensor networks may be the best tool currently available for rigorous ecological valuation. Continued research on the performance and enhancement of WSNs for forest productivity monitoring is needed and promises to lend itself as a valuable resource for well-informed forest management practices.

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TABLES LEGENDS

TABLE 2-1. RSSI linear regression coefficient contributions for each predictor and season.

FIGURE LEGENDS

FIGURE 2-1. WSN Study plot is located in north-western Alberta, Canada in an old growth stand of deciduous boreal forest.

FIGURE 2-2. WSN hexagonal topology for optimal light sensor field of view coverage. Network data aggregator is located outside the forest in the clearing. Nodes used in the analysis are found in rows r1-r4 at left (L), center (C) and right (R) columns indicated by line transects to refer to node locations (ex. r1R).

FIGURE 2-3. Wireless environmental monitoring sensor node for forest micro-meteorology and phenology.

FIGURE 2-4. Time series of temperature and photo-synthetically active radiation (PAR) from one node in the sensor network.

FIGURE 2-5. Seasonal trend in canopy greenness (NDVI) measured using the WSN canopy phenology nodes. Leaf expression begins in May and ends in November.

FIGURE 2-6. Time series of the daily mean RSSI for each node and for the average across the sensor network for the spring, summer, and fall of 2013. General seasonality can be seen for the 220-day period. Node r1L showed a drastic unexplained drop at the beginning of June and was excluded from the network mean.

FIGURE 2-7. Seasonal variability in the mean network RSSI from April to November 2013. A shift towards lower RSSI values occurs with canopy development.

FIGURE 2-8. WSN node-base layout with slant RF propagation through two layers of dense foliage separated by woody area only. Plot rows R1-R4 separated by 20m.

FIGURE 2-9. Seasonal RSSI distributions for three nodes in A) row 1 nearest to the receiver and B) row 4 furthest from the receiver.

FIGURE 2-10. Relative importance assessment of linear regression model components using four decomposition methods for daily A) mean and B) mean variance in network link RSSI for the entire growing season April 20 to November 30, 2013. A) df=211, adjusted R^2=0.67, p<0.001; B) df=211, adjusted R^2=0.43, p<0.001.

FIGURE 2-11. Mean RSSI regressor importance for the whole season (SE ±1.9 dBm) and each sub-season

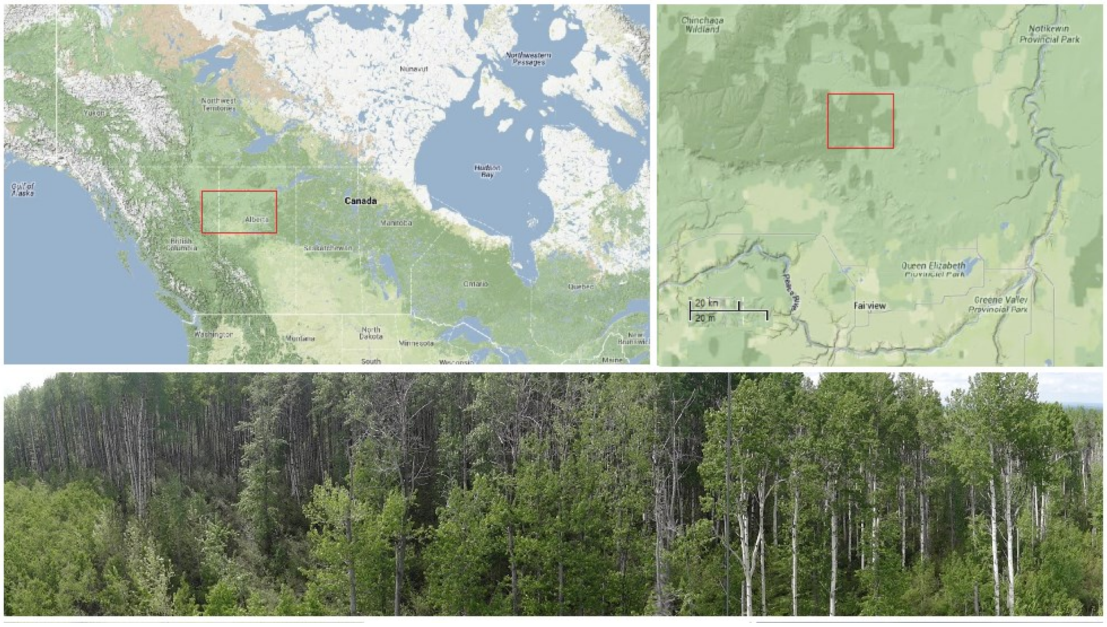
(TABLE 2-1)

RSSI Timeframe	**Percent Contribution to Linear Model R^2 [a]**						
	fAPAR	*NDVI*	*T*	*VPD*	*SR*	*WND*	***% R^2***
All Season μ	9	**34**	29	9	12	6	**67.7**
Green Up μ	27	**35**	27	5	3	4	**88.0**
Maturity μ	1	18	**64**	12	3	3	**54.4**
Senescence. μ	4	**50**	14	9	18	5	**51.7**
All Season σ^2	2	11	**62**	12	12	1	**44.6**
Green Up σ^2	15	18	18	**24**	8	17	**35.0**
Maturity σ^2	2	2	10	10	2	**74**	**18.0**
Senescence σ^2	10	22	**45**	10	10	3	**53.7**

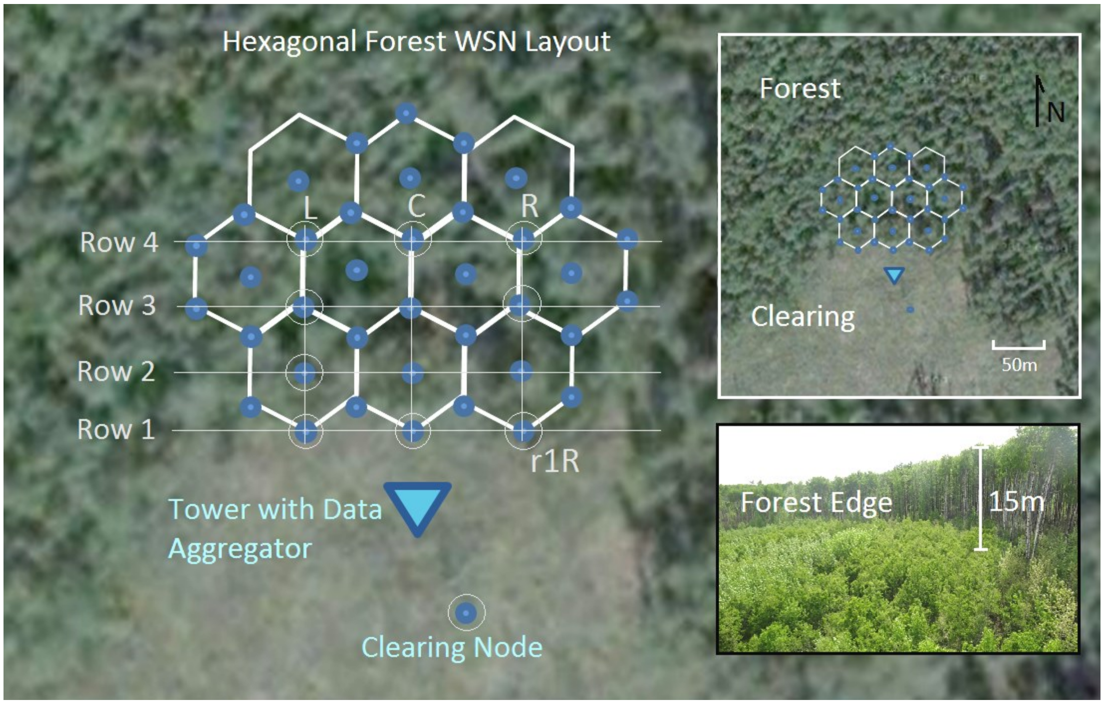
[a.] Based on bootstrapped LMG relative importance model

[b.] Bold numbers are the highest correlation for each regressor

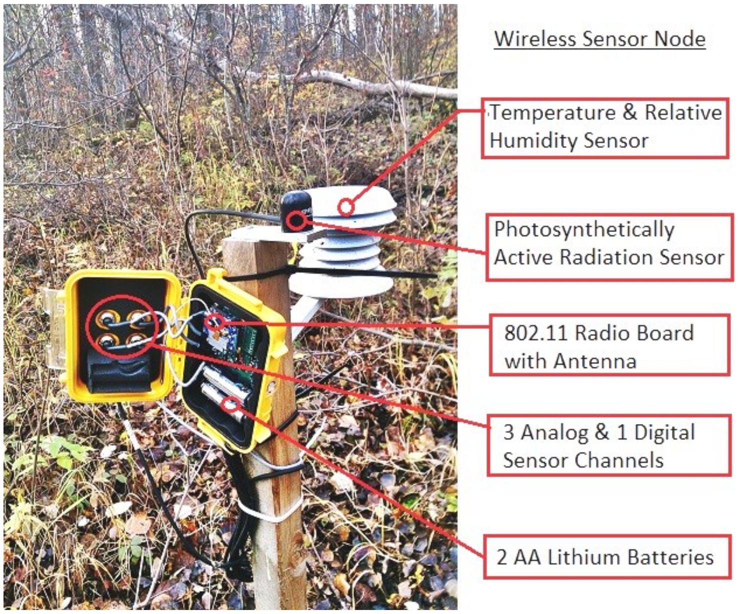
(FIGURE 2-1)



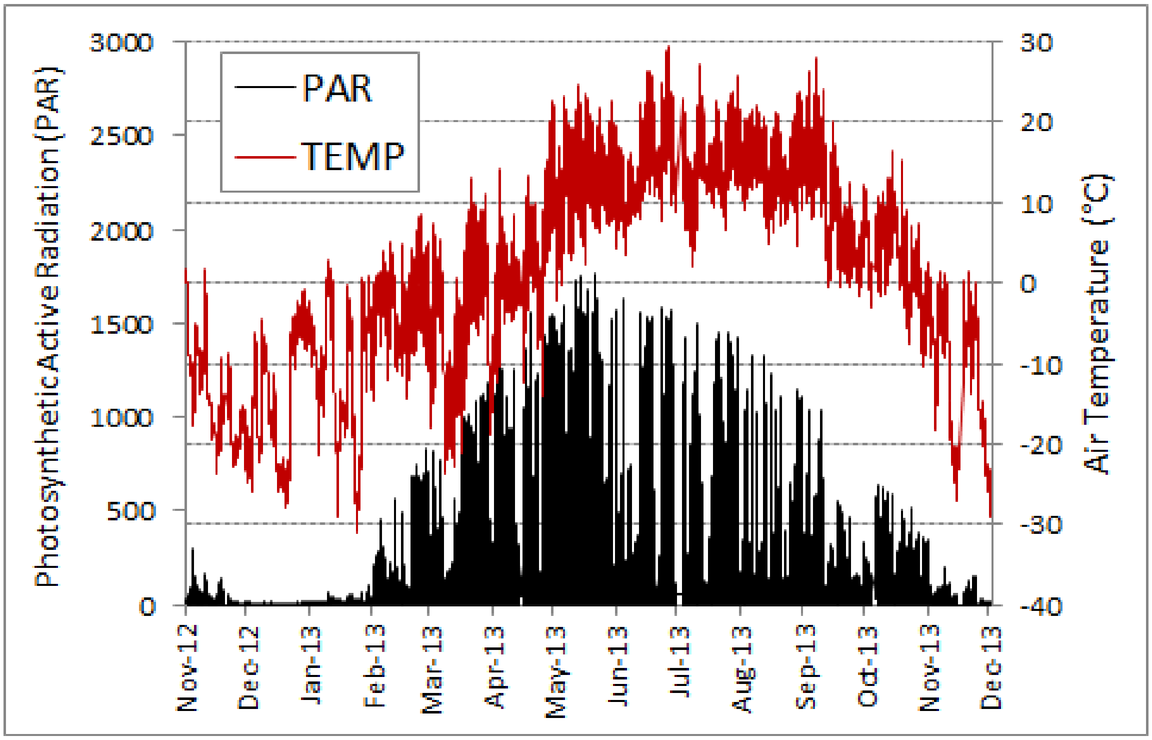
(FIGURE 2-2)



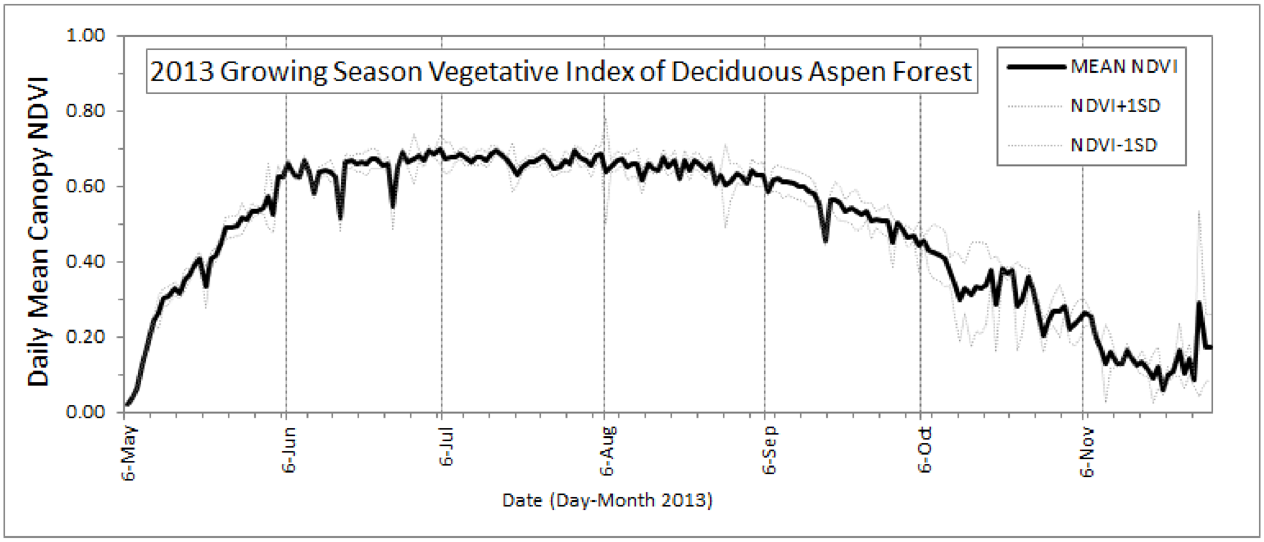
(FIGURE 2-3)



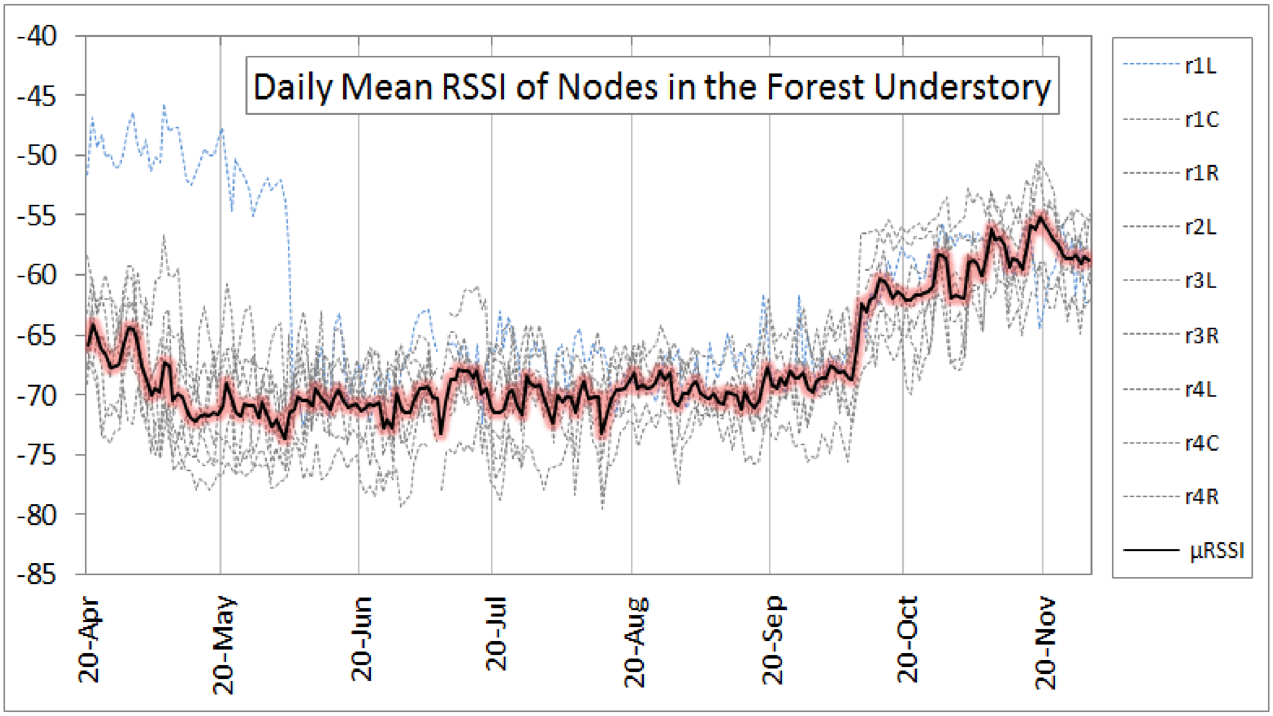
(FIGURE 2-4)



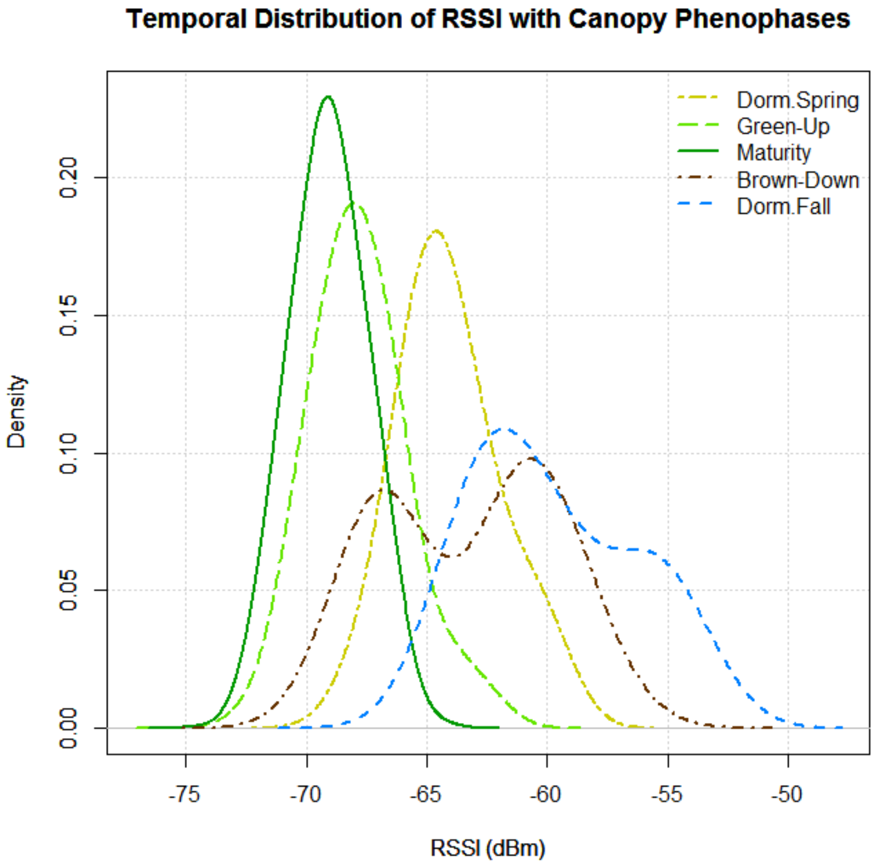
(FIGURE 2-5)



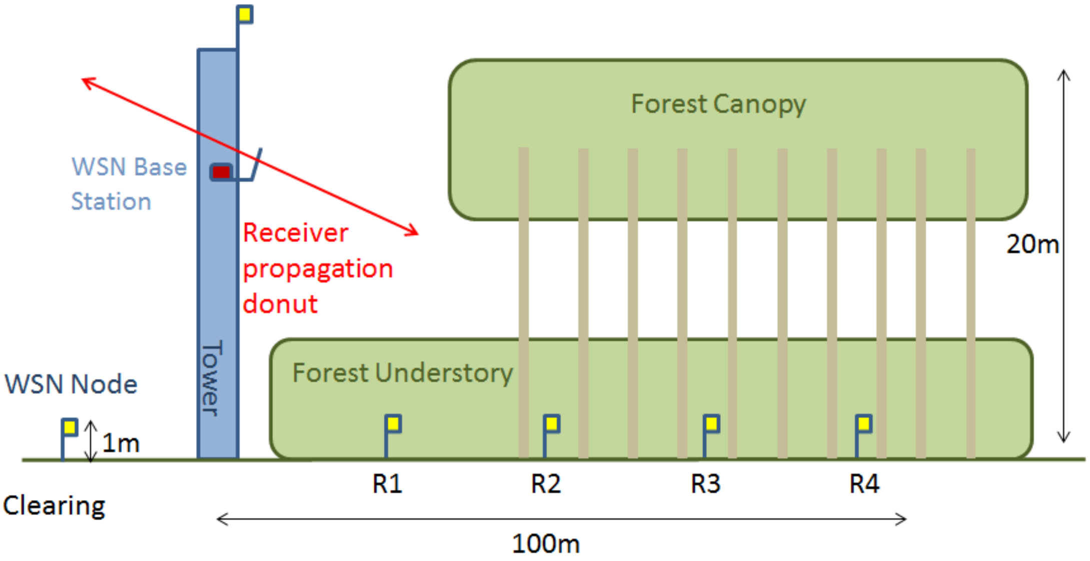
(FIGURE 2-6)



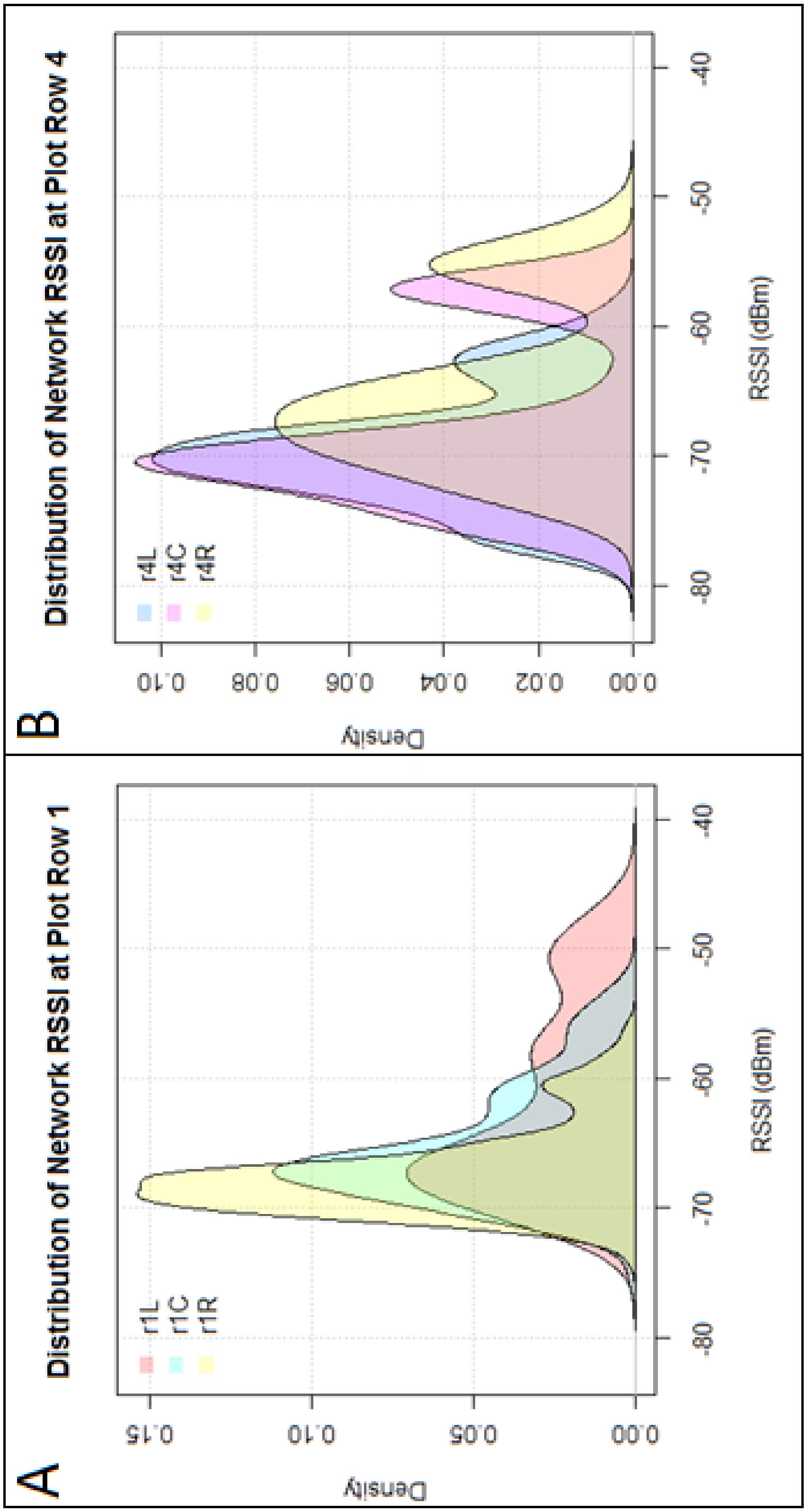
(FIGURE 2-7)



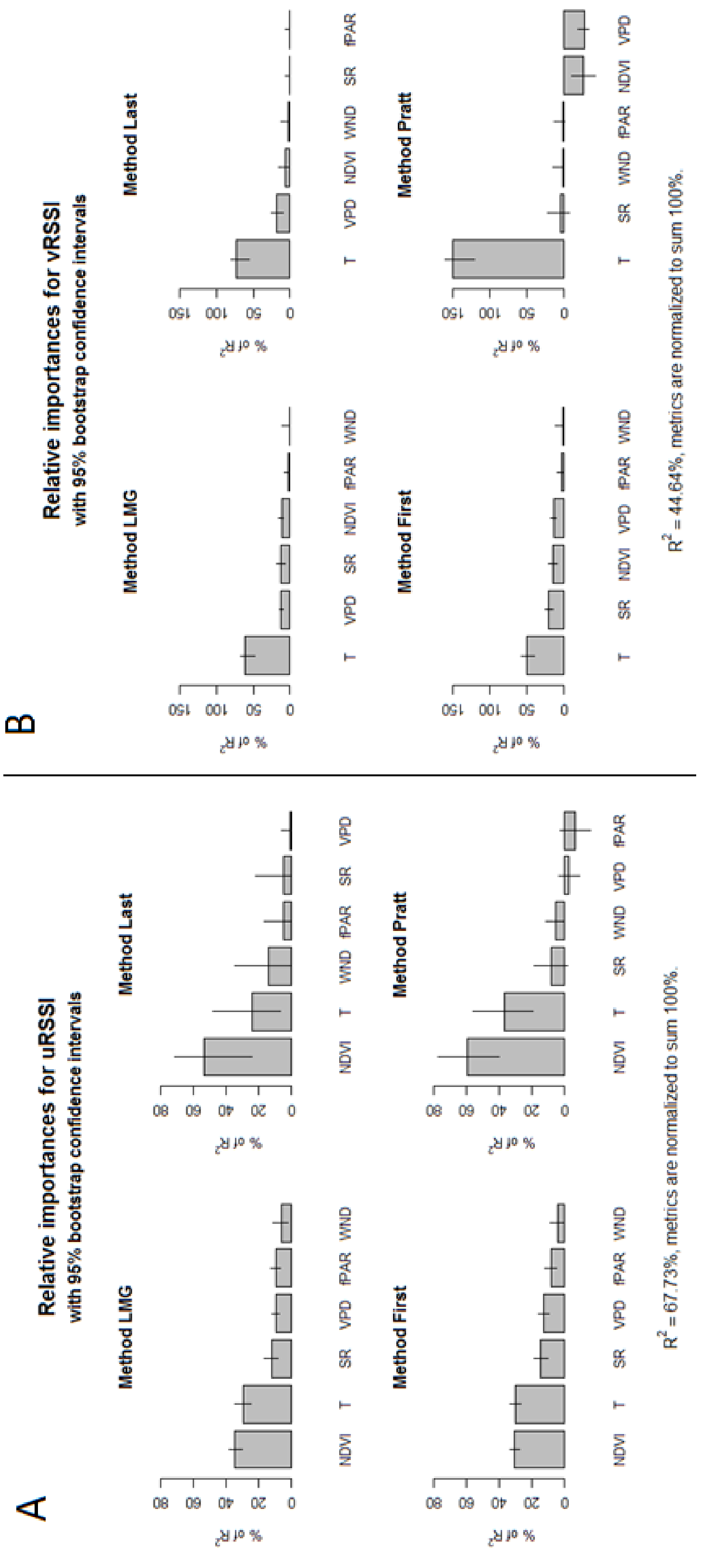
(FIGURE 2-8)



(FIGURE 2-9)


A
Distribution of Network RSSI at Plot Row 1
r1L
r1C
r1R
Density
0.00
0.05
0.10
0.15
RSSI (dBm)
-80
-70
-60
-50
-40
B
Distribution of Network RSSI at Plot Row 4
r4L
r4C
r4R
Density
0.00
0.02
0.04
0.06
0.08
0.10
RSSI (dBm)
-80
-70
-60
-50
-40

(FIGURE 2-10)


A
Relative importances for uRSSI
with 95% bootstrap confidence intervals
Method LMG
Method Last
Method First
Method Pratt
% of R²
0
20
40
60
80
NDVI
T
SR
VPD
fPAR
WND
NDVI
T
WND
fPAR
SR
VPD
NDVI
T
SR
VPD
fPAR
WND
NDVI
T
SR
WND
VPD
fPAR
R² = 67.73%, metrics are normalized to sum 100%.
B
Relative importances for vRSSI
with 95% bootstrap confidence intervals
Method LMG
Method Last
Method First
Method Pratt
% of R²
0
50
100
150
T
VPD
SR
NDVI
fPAR
WND
T
VPD
NDVI
WND
SR
fPAR
T
SR
NDVI
VPD
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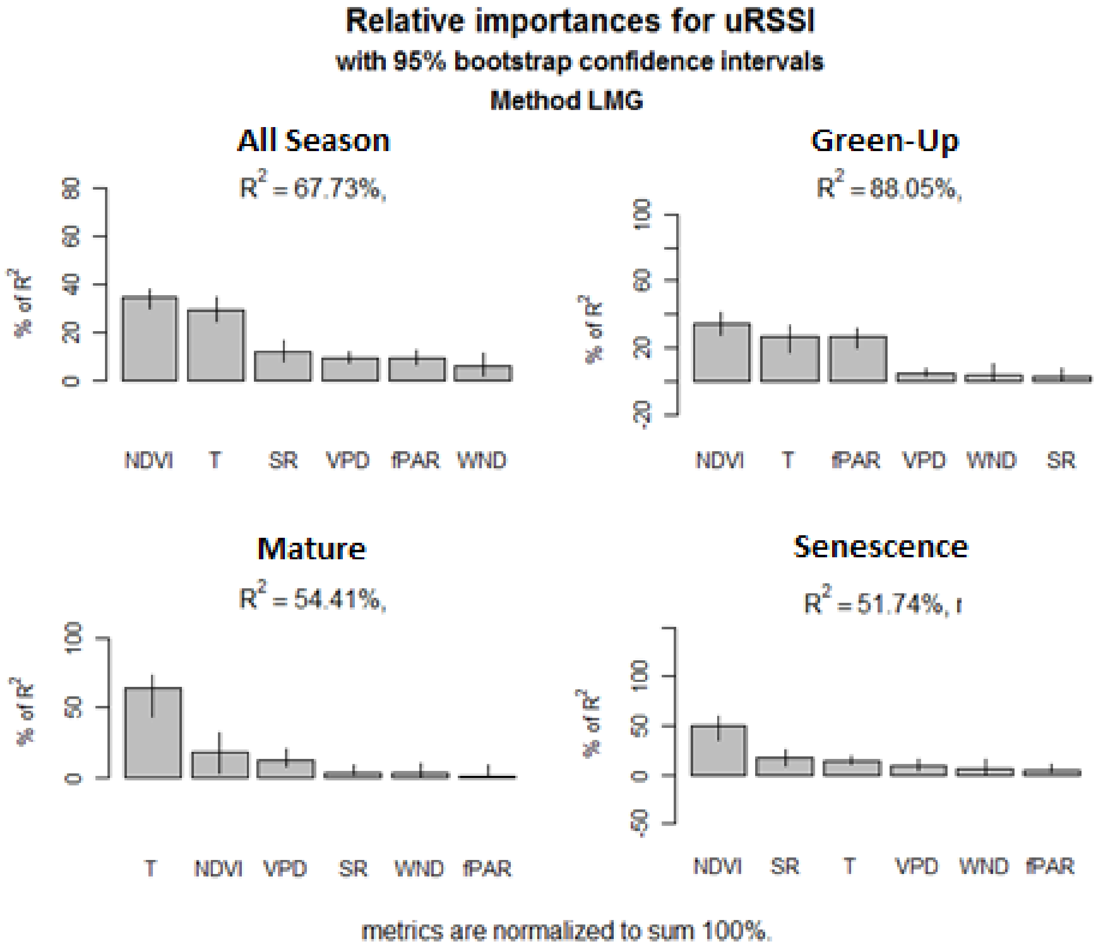
WND
T
SR
WND
fPAR
NDVI
VPD
R² = 44.64%, metrics are normalized to sum 100%.

(FIGURE 2-11)


Relative importances for uRSSI
with 95% bootstrap confidence intervals
Method LMG
All Season
R^2 = 67.73%,
% of R^2
0
20
40
60
80
NDVI
T
SR
VPD
fPAR
WND
Green-Up
R^2 = 88.05%,
% of R^2
-20
20
60
100
NDVI
T
fPAR
VPD
WND
SR
Mature
R^2 = 54.41%,
% of R^2
0
50
100
T
NDVI
VPD
SR
WND
fPAR
Senescence
R^2 = 51.74%, r
% of R^2
-50
0
50
100
NDVI
SR
T
VPD
WND
fPAR
metrics are normalized to sum 100%.

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CHAPTER 3

SUCCESSION AND SEASONALITY OF A BRAZILIAN TROPICAL DRY FOREST: PHENOLOGY AND CLIMATE MODERATION IN SECONDARY STANDS

ABSTRACT

Tropical dry forests (TDFs) are a globally threatened ecosystem rich in ecosystem services that support the livelihoods of millions of people in the tropics and sub-tropics. Large areas of TDFs in the Neotropics are currently undergoing secondary succession and require an better understanding of how ecosystem functions recover in relation to forest regeneration. TDF contributions to land-atmospheric carbon, water, and energy cycling are often overlooked and poorly understood, in part due to a lack of empirical data on TDF canopy-climate interactions. In this study I present observations and correlations between seasonal changes in local meteorological conditions and high temporal resolution tower-based optical canopy phenology time series in an early (10-12 years) and late (50+ years) successional stage TDF in southeastern Brazil. Results suggests a minimum precipitation of 100 mm within two weeks during the onset of the rainy season to initiate leaf flushing in this TDF. Soil moisture and daytime air humidity strongly correlated ($R^2 > 0.75$) with seasonal patterns in canopy vegetation greenness indices and the fraction of Absorbed Photosynthetic Active Radiation (*f*APAR), with a cross-correlation time lag peak of 12-15 days. These meteorology-phenology relationships were slightly stronger in the younger forest stand. Diurnal and seasonal patterns of understory microclimates are further compared between stand age plots and investigate the strength of forest canopy climate moderating capacity (CMC) - the difference between below-canopy and open area micrometeorological conditions. The mature TDF canopy was, on average, 30-50% more effective at cooling (-1.4 ± 0.6 °C vs -0.8 ± 0.6 °C) and reducing daytime evaporation potential (-0.41 ± 0.2 kPa vs -0.18 ± 0.12 kPa) in the understory during the growing season compared to the young forest. The CMC varied with seasonal canopy leaf area dynamics as well as with heat and moisture scales, becoming significantly stronger when temperatures and vapour pressure deficits were highest, and correlated strongly with canopy *f*APAR dynamics ($R^2 = 0.82$). These findings demonstrate that these important tropical ecosystems

can effectively regain microclimatic buffering capacity relatively quickly despite lower structural complexity and species richness during early succession which emphasizes the need to include canopy-climate moderation as a tangible ecosystem service in TDFs, subject to seasonality and inter-annual variations in phenology. Overall, the seasonal dependence of microclimate ecosystem functions on water availability and canopy leaf phenology is explicitly quantified, relating short and long term structural dynamics of the forest canopy to functional diversity in secondary TDF landscapes.

INTRODUCTION

Secondary Neotropical Dry Forests

Nearly half of the world's tropical forest are seasonally dry with little to no rainfall for several months of the year. These Tropical Dry Forests (TDFs) cover an estimated 1,048,000 km^2 globally (Miles et al. 2006) but are thought to have historically been much more expansive. Hoekstra et al. (2005) estimate 48% of the original TDF extent has been converted for human land use. TDFs tend to experience greater rates of human settlement and disturbance than wet tropical forests due to their fertile soils for agriculture, flat topography, and favorable climate, in addition to the many useful natural resources produced by the forests themselves. Over the last century TDF ecosystems have endured extensive deforestation, fragmentation, and degradation from increased anthropogenic pressures, and are currently considered the most threatened tropical ecosystem.

The Americas are home to over 50% of the remaining TDFs (Miles et al. 2006), with South America alone containing 268,800 km^2 (Portillo-Quintero & Sanchez-Azofeifa 2010). An increased demand for agricultural lands and shifts in land use policies/incentives drove much of the deforestation in Latin America in the late 20th century resulting in a potential 60-70% loss in TDF ecosystems (Portillo-Quintero & Sanchez-Azofeifa 2010). Agricultural land in the Neotropics is frequently abandoned and left to fallow after overuse or due to changes in economic drivers and policies, leaving the forest to regenerate naturally. With vast areas of tropical dry forests in various stages of secondary succession in the 21st century there are many questions as to how quickly these seasonal forests can regain their ecological functions to once again perform valuable ecosystem services.

Tropical deforestation and land cover changes research has focused largely on processes of structural recovery and biomass accumulation of secondary tropical forests due to the important role they play as global atmospheric carbon sinks (Brown & Lugo 1990; Martin et al. 2013), but far less attention has been given to understanding how secondary forest ecosystems function during and after natural regeneration (Guarigata & Ostertag 2001). TDFs serve many useful environmental functions and ecosystem services including flood mitigation, soil stabilization and generation, water cycling and purification, carbon sequestration, timber, fuel, fibre and food production, and biodiversity preservation (Farrick and Branfireun 2014; Cotler and Ortega-Larrocea 2006; Brauman et al. 2007; Maas et al. 2005). While tropical forest structure and plant biomass may recover quite quickly, over a few decades, ecosystem functions and important services dependent on plant and animal biodiversity tend to take much longer to return to pre-disturbance levels (Gibson et al. 2011; Martin et al. 2013). However, functional characteristics related to forest structure can be reproduced prior to attaining the plant diversity of a climax forest community due to the ecological functional redundancy of plant species (Walker 1992). For example, young and intermediate stage secondary tropical forests may produce high canopy leaf areas despite low tree species richness and intercept enough sunlight to cool the understory and reduce soil moisture loss similar to an old growth forest. Unlike tropical moist forests, where canopy structure and function can be seasonally de-coupled, tropical dry forests tend to demonstrate strong seasonal coupling between canopy leaf structure, photosynthetic activity, and ecosystem functions (Guan et al. 2013).

Climate and TDF Phenology

Strong seasonality in TDFs means that many of their ecosystem services are only functional for part of the year when the canopy is photosynthesizing and leaf area is high. This is a key motivation to understand what external abiotic drivers control leaf expression and canopy photosynthetic capacity in tropical dry forests. TDFs are highly synchronized with their environment and have well-adapted life cycle dynamics to changing weather conditions. In the moist tropics, evergreen forests do display some patterns of seasonal leaf flushing and abscission, but this tends to be weakly associated with water resources and more dependent on photoperiod and total available photosynthetic radiation (Wright and Schaik, 1994). In contrast, the leaf phenology of TDFs has been shown to be primarily controlled by moisture availability (Reich 1995; Do et al. 2005; Yoshifuji et al. 2006; Valdez-Hernandez et al. 2009;) and showcases strong seasonal leaf area dynamics ideal for satellite and near-surface remote sensing observation (Sanchez-Azofeifa et al, 2003). While the phenology of TDFs has been reasonably well characterized by ground observations, these are typically manually made observations with long sample intervals that tend to end after one or two seasons. Furthermore, studies that relate vegetation phenology in TDFs to meteorological conditions often rely on regional meteorological records that may be incomplete, infrequent, or biased by significant spatial variability between forest study sites and measurement locations.

As climate change in the 21st century is thought to bring with it greater uncertainty in global precipitation patterns, South America in particular may be at significant risk from changes in rainfall distribution and intensity (Marengo et al. 2014). Miles at al. (2006) suggest that the largest threat to TDF conservation in Latin America will be climate change in the coming decades. Unfortunately, very little is currently known about the precise drivers and responsivity of TDF phenology to climate variability. Given such a lack of understanding on the future resilience of TDFs in relation to climate forcing, we are left with many questions regarding patterns of climate sensitivity with respect to TDF phenology in South America, where a large portion of these remaining forests are found. For example, are there precipitation or soil moisture thresholds that trigger TDF leaf flushing and how quickly does the forest respond? What degree of water stress triggers leaf abscission? Can unseasonal rainfalls induce a second growing season in continental TDFs as they have been known to do so in coastal TDFs? Are there asynchronies between TDF understory and overstory phenology that may produce errors in satellite-based phenology observations? And finally, do early, late stage, and old growth TDFs behave differently to all of these situations? Since ecosystem services of TDFs relate strongly to their phenology, it is important to understand if we need to assess climate variability impacts on phenology differently between young and old TDFs as secondary forests play an increasingly vital role in the agro-landscape of the Neotropics.

TDF Succession and Microclimate

When agricultural land is abandoned and left to fallow in the tropics, the pioneer plant species that colonize first tend to be well adapted to harsh climates, nutrient depleted substrates, and generally poor growing conditions. As plant community succession progresses, the ecosystem becomes self-servicing as larger plants create more favorable microclimates for new species to grow, starting a positive feedback process that eventually supports the establishment of late succession species. Since the process of tropical forest succession relies on changes in below-canopy abiotic conditions, the rate of these climate moderation processes are significant drivers of species turn-over and successional progression. In TDFs, the pronounced seasonality of rainfall and high moisture deficits means that microclimate niche generation is vital to seedling establishment in early successional stages. Unfortunately, very few studies have attempted to quantify the climate moderating capacity (CMC) of secondary TDFs.

In regions where TDFs preside the total evapotranspiration typically exceeds precipitation and the plant available water is largely driven by local meteorological conditions such as light, heat, humidity, and wind. This plant-water supply and demand is further moderated by the forest itself based on canopy and understory structure. Canopy roughness, tree height and density will affect wind speed, which in turn affects rates of evapotranspiration and cooling (Thom 1972). Forest canopy closure and leaf area affect light penetration, a fundamental driver of understory microclimates, namely air and soil temperature and moisture dynamics. Below-canopy microclimate gradients can play a significant role in modifying soil and air moisture availability which can modify plant productivity and habitat diversity (Hunter 1999). The only study to our knowledge that examine below-canopy microclimate dynamics in TDFs as a function of succession was by Lebrija-Trejos et al. (2011). Their results suggest that, unlike tropical moist forests, understory temperature and humidity gradients were more important to secondary succession processes in TDFs than light availability. A better understanding of the critical factors for seedling establishment and survival in young TDFs and tree recruitment in mature TDFs is necessary in order to predict and model the forces of balance between forest loss and regrowth.

In this study I ask the question, how does secondary forest stand age affect its functional ability to moderate temperature and moisture extremes? I explore the relationships between high frequency observations in seasonal meteorology and canopy phenology, understory microclimates, and canopy moderating capacity (CMC) comparing two secondary TDF stands at different successional stages. I examine the canopy moderation capacity dynamics of an early stage and mature TDF to see how well a 15-year-old TDF buffers temperature extremes and retains water vapour compared to its more mature counterpart. I further address some of the uncertainties surrounding the extent of synchronization between TDF phenology, meteorology, and successional stage in the context of revealing seasonal changes in ecosystem functions in secondary TDFs.

MATERIALS & METHODS

Study Site

This study was conducted at the Mata Seca State Park, hereafter referred to as MSSP (14.78 to 14.95 S and 44.04 to 43.93 W), which is situated just to the west of the Sao Francisco River in the Manga municipality on the northern border of Minas Gerais state in southwest Brazil (Figure 3-1). MSSP is a conservation area of 15,460 ha with restricted public access. Soils in the park are nutrient rich and the landscape is predominantly flat with drainage northwest towards the river. The MSSP is predominantly dominated by TDFs. Sanchez-Azofeifa et al. (2005) defined TDFs as those forests that are dominated by deciduous vegetation with at least 50% tree cover, where the mean annual temperature is 25°C or greater, total annual precipitation is between 700mm and 2000mm and having three or more consecutive months of the year with less than 100mm of rainfall. The park's climate is tropical semi-arid (Koppen's classification) with a mean annual precipitation of 818 ± 242mm (mean ± standard deviation for 70 years of manual observations in nearest town) which is relatively wet for a semi-arid region, providing sufficient moisture to support the tropical dry forest. Pronounced rainfall seasonality in the park reveals over 90% of the rain falls between October and April. The severe drought between May and September causes the predominant broadleaf trees of the forest to drop over 90% of their foliage during the dry season as a water stress avoidance strategy. Mean annual temperature in MSSP is 24.5 ± 0.8 °C with seasonal nighttime minima reaching as low as 8°C in July and seasonal daytime maxima between 35°C to 40°C at the end of the dry season in October.

The region is currently a human dominated agro-landscape with extensive cattle pasture and irrigated farmland that support local populations and neighboring regions, with patches of secondary and primary tropical dry forest, some of which are now protected. The MSSP is one of several conservations areas protected from deforestation in response to the World Bank's Jaiba Irrigation Project that funded the development of nearly 200,000 ha of irrigated farmland from 1998 to 2000 in an effort to alleviate drought-related poverty and promote socio-economic growth in the region (Sevilha et al. 2004). Roughly 1,500 ha of MSSP is comprised of abandoned pasture with naturally regenerating TDFs of various successional stages with the remaining majority of the park being secondary and primary forest.

Sample Plots and Instrumentation

There were three sites within MSSP used in this study, an open-area reference meteorological station located on the east side of the park which was used as the experimental control (14.85 S, 43.94 W, 460m), a mature tropical dry forest located in the middle of the park 4.9km west of the control station (14.84 S, 43.98 W, 480m), and a young secondary forest stand 6.9 km west of the control station (14.85 S, 44.00 W, 470m). The reference weather station is located near the main research station on a manicured grass field (hereafter referred to as the field reference) at least 50 m from nearby structures and over 100 m from the nearest forest edge. Land use records indicate the young tropical dry forest (yTDF) stand was used for cattle pasture for at least 20 years with annual slash and burn management, then abandoned in 2000 and left to regenerate naturally. There are no records of the mature tropical dry forest (mTDF) stand being clear-cut in the last 50 years but this does not exclude the possibility of selective logging prior to the year 2000.

The successional stage of these sites were categorized based on stand age as well as the horizontal and vertical structure of the forest based on the approach of Kalacska et al. (2004; 2005). Both forests have two vertical vegetation strata: the mature forest has an heterogeneous 18-24m tall closed tree canopy with a 1-2m tall understory of woody herbaceous plants, tree saplings, and abundant lianas, the young forest has a partially-open but uniform height overstory canopy (5-7 m tall), a low liana density, and a low lying understory of grasses, shrubs, and young saplings (Figure 3-2). Basal area of the yTDF and mTDF plots were 3.1 ± 0.8 m^2 ha^{-1} and 22.0 ± 6.4 m^2 ha^{-1}, respectively, for trees >5 cm diameter at breast height. Information on tree species composition and richness for these plots can be found in Madeira et al. (2009).

All three sites had meteorological stations measuring air temperature (T_{air}) and relative humidity (RH) (Onset S-THB-M008), rainfall (Onset S-RGA-M002), incident shortwave solar radiation (Onset S-LIB-M003), incident photosynthetically active radiation, or PAR (Onset S-LIA-M003), and volumetric soil water content (Onset S-SMC-M005) sampling every 30 seconds and logging the 30 minute means (Onset HOBO microstation loggers). The field reference ambient air temperature and humidity were measured at 1.25 m above the ground (following World Meteorological Organization guidelines) and soil water content sensors were placed at 15cm depth. The vapor pressure deficit (VPD) of the air was derived from air temperature and relative humidity using the water vapor partial pressure equation by Goff and Gratch (1946).

Forest study plots of 50m x 50m (0.25 ha) were created at least 100m from the nearest forest edge, to minimize microclimatic edge effects, which were shown by Portillo-Quintero (2014) to extend up to 100m from a forest edge in MSSP. The forest plots were each instrumented with a wireless sensor network (WSN) of 12 synchronized micrometeorological sensor nodes (custom hardware development by Olsonet Communications®). Nodes were spaced 15 m apart along four transects that intersected at the center of the 0.25 ha plot, known as a star-topology, so as to provide sufficient spatial sampling, reduce sample bias of any single understory location, and to estimate spatial variability of below-canopy microclimate with high temporal synchronization of samples. WSN nodes measured air temperature, relative humidity, and down-welling PAR at 1m height. Plot replicates of forest stand ages were not possible due to the cost-prohibitive nature of installing and maintaining large long-term sensor network arrays (Corke et al. 2010), nevertheless, Lebrija-Trejos et al. (2010) found that TDF successional trajectories showed high consistency in species composition and forest structure between plots across a large stand age chronosequence, with similar land-use history.

The study sites also had instrumented canopy towers for synchronized bi-directional hemispherical incident and reflected PAR and total shortwave radiation fluxes following the methods by Wilson and Meyers (2007) for deriving the in-situ Normalized Difference Vegetation Index (NDVI) and the two-band Enhanced Vegetation Index or EVI2 (Jiang et al. 2008) using broadband radiometric sensors (silicon quantum sensors and pyranometers). The nadir-facing hemispherical optical sensors projected a circular viewing footprint of roughly 100 m diameter for canopy radiometric reflectance time series of leaf phenology. In addition, understory wireless sensor networks were equipped with PAR sensors to measure transmitted light and ultimately the fraction of canopy absorbed PAR (*f*APAR) which is a useful structural and biophysical plant canopy parameter and indicative of plant canopy photosynthetic capacity and leaf area index (LAI) (Maass et al. 1995; Fensholt et al. 2004). Equations for calculating the NDVI, EVI2, and *f*APAR are as follows:

$$NDVI_{Tower} = (R_{NIR} - R_{VIS} / R_{NIR} + R_{VIS}) \tag{1}$$

$$EVI2_{Tower} = 2.5 * R_{NIR} - R_{VIS} / (R_{NIR} + (2.4 * R_{VIS}) + 1)) \tag{2}$$

Where R_{NIR} and R_{VIS} are canopy reflectance in the near infrared and visible light wavelengths, respectively, as estimated from broadband PAR and total solar radiation radiometric sensors following Wilson and Meyers (2007).

$$fAPAR_{3\text{-}flux} = (iPAR - rPAR - tPAR) / iPAR \tag{3}$$

Where *i*PAR is incident PAR above the canopy, *r*PAR is reflected PAR above the canopy, and *t*PAR is downwelling par transmitted through the canopy measured at 1m above the forest floor, averaged across the 12 understory PAR sensors over the 2500 m^2 sampling area in each plot. *f*APAR measurements were averaged across daylight hours. Furthermore, an 8 megapixel time-lapse camera was set up in the understory of both forest plots, taking photos each hour from 9:00 to 15:00 in order to verify the leaf status of the trees and detect onset of budburst and leaf flushing.

All the time series data was uploaded to the project's online database cyberinfrastructure, Enviro-Net ® (Pastorello et al. 2011; www.enviro-net.org), for advanced data management including on-demand visualization, curation, sharing and retrieval for raw and filtered time series data. This web-enabled database further allows for real-time generation of vegetation indices and PAR biophysical products based on the optical phenology algorithms described in equations 1-3.

Data Analysis

Time Series Processing

This study ran from mid-season 2008 to the end of 2014, but due to high instrument failure rates, the focal time period of observation used in this study runs from August 1, 2011 to September 15, 2013 and includes two full growing seasons, or hydrological years, of the forest. For this period, daily mean midday vegetation index values were derived using observation between 10:00 and 14:00 hours and with a minimum incident PAR value of 1000 uE to restrict the observations to near nadir solar zenith angles and direct 'black' sky illumination conditions only (Wilson and Meyers, 2007). Meteorological time series data were also aggregated to daily mean values for comparison and long-term trend overview. Since the influence of meteorological conditions on deciduous tree physiology will differ depending on leaf life-cycle period, part of the analysis was separated into the four canopy leaf phenology phases (phenophases), green-up, maturity, senescence, and dormancy (Zhang et al. 2003). The key phenophase transition dates are marked by the onset of greenness increase, onset of peak greenness, onset of greenness decrease, and onset of greenness minimum in the greenness time series curve. First, the phenology curves were smoothed using spline interpolation (smoothing factor: NDVI = 0.3, EVI =0.5) to remove excessive signal noise and fill small gaps where data was missing for no more than three consecutive days. Phenology transition dates were then selected based on the second order derivatives of the smoothed NDVI/EVI time series finding the local maxima and minima of the differentiated time series function which correspond to the greatest rates of change in the greenness curve and indicating the onset of each phenophase period. For different temporal subset analysis our definition of daily mean values includes measurements across the full 24 hour periods, daytime mean values refer to measurements retrieved between sunrise and sunset hours, and midday means refer to the hours between 10:00 and 14:00, when temperatures typically peak in the tropics and greater spatial variability in understory light and related microclimates tend to emerge.

Correlating Meteorology and Forest Phenology

To explore the correlation between near-surface vegetation greenness indices, the fraction of canopy absorbed PAR, and local meteorological variables during the growing season for both the young and mature forest sites the Spearman coefficient was used for nonparametric data given the temporal auto-correlative nature of the time series data. The adjusted p value, based on the Holm's method, was used to assess correlation significance. The full growing season extent, from the start of green-up to end of senescence and excluding the canopy dormancy period, was isolated for each season then compared between the two hydrological years, 2011/2012 and 2012/2013. In addition, both green-up and senescence phenophase periods were individually compared. Daytime averages were used for all meteorological variables except for rainfall, for which daily sum rainfall was used, and the 10-day moving average of the daily precipitation sum, which is referred to as 10d-Rain and indicates short-term accumulated rainfall. Furthermore, given the temporal lag between meteorological changes and canopy leaf flushing resulting from well-adapted risk-avoidance strategies in tree phenology during the dry to rainy season transition, a cross-correlation analysis was run for the canopy green-up period to determine the time-lag response of the forest to water availability. The base stats package in R statistical software was used for data analysis (R Development Core Team 2012).

Seasonal and Diurnal Microclimate Comparisons

Temporal patterns and spatial variability of understory air temperature, relative humidity, VPD, and transmitted PAR were compared between the sites and within the wireless sensor networks. Trends were plotted as a function of diurnal and seasonal cycles by taking the mean hourly and mean monthly values, respectively, for the peak wet season and peak dry season months from each sensor node and averaged for both observation years. Seasonal periods are described as either wet season and dry seasons, referring to the drought seasonality, or as leaf-on and leaf-off state, referring to the maturity and dormancy canopy phenology phases. Differences in spatial variability within the sensor networks between forest plots were assessed using paired t-tests for each micrometeorological variable. The interaction effect between measurement site, leaf state, air temperature, and vapour pressure deficit was tested using multiple two-factor analysis of variance with site and leaf state as the independent factors and the microclimate data as the dependent variables. Model assumptions were all tested and met (Shapiro-Wilks test for normality and residual analysis). Post-hoc differences were assessed using the Tukey Honest Significant Difference (HSD) test based on the adjusted p-value < 0.01.

Canopy Moderating Capacity

In order to calculate the canopy moderating capacity (CMC) of understory heat and moisture, the T_{air} and VPD of the understory stations were subtracted from the corresponding measurements in the open field control station.

$$CMC_{Variable\ X} = Variable\ X_{Open\ Area} - Variable\ X_{Below\ Canopy} \qquad (4)$$

In the tropics, excessive overheating and dehydration are difficult to overcome during drought periods, thus positive CMC values indicate a desirable moderation effect and negative values represent immoderation (i.e. hotter or drier). Then to see how the CMC differed between forest age stands and as a function of canopy phenology, the daytime mean and maximum air temperature and VPD CMC time series were separated by site and phenophase and tested for seasonal trends. In addition, daytime mean T_{air} and VPD for each site were plotted against their corresponding CMC values to reveal any effect of scale magnitude on the extent of CMC during the growing season. Daytime maximum T_{air} and VPD were also plotted against canopy *f*APAR time series at each site combining both years (n = 717) to examine any relationship between canopy biophysical dynamics and below-canopy climate moderation. Linear and second order polynomial regression analysis was performed and evaluated based on the adjusted p-value and model residual standard errors (RSE). Once again, all statistical assumptions were tested and met.

RESULTS & DISCUSSION

Patterns of Meteorology and Phenology

As the dry winter months from April to October transition into summer the solar insolation increases, it is the only time of the year that the daily mean air temperature at the control station rises above 30 °C, and the daily mean relative humidity drops to less than 50% (Figure 3-3). During this seasonal peak in heat and drought conditions, the midday and afternoon vapor pressure deficit often exceeded 4 kPa. This is extremely demanding on plant water balance considering the optimal VPD for most plants ranges from 0.5 to 1.3 kPa, based on measurements of greenhouse productivity. These highly arid atmospheric conditions often immediately precede the onset of the rainy season and the annual leaf flush of the forest vegetation.

With the arrival of the first heavy rainfall of the wet summer season, there is a dramatic and sustained increase in relative humidity along with a decrease in air temperature and VPD (Figure 3-3). For example, in the first week of November of 2012 the daily mean VPD transitioned from 3.0-3.5 kPa to less than 0.5 kPa. What is more notable about this transition is that the rapid drop in VPD occurs several days prior to the first rainfall (Figure 3-4). This drastic pre-rainfall shift in atmospheric vapour pressure was shown to be a consistent pattern across seven years of meteorological observations and may be considered the first physiologically relevant event capable of triggering bud burst and the onset of leaf flushing in this continental tropical dry forest.

Based on the phenology camera and vegetation greenness time series, leaf budburst began precisely after the first 128 mm and 110 mm of rainfall were measured in 2011 and 2012, respectively. This occurred ten days following a minimum 15-20% increase in soil moisture for the 2011 and 2012 green-up events, and 20 days were required for full leaf expansion and forest canopy development. The rapid leaf expansion of the forest resulted in an NDVI increase from 0.53 to 0.84 and a doubling of the EVI2 from 0.3 to 0.6 for the mature forest. The young forest had the same NDVI annual minima but a slightly lower NDVI peak than the mature forest, reaching a 3% and 8% lower amplitude in the first and second year. Consistent differences between young and old forest greenness was not observed for the EVI2 (Figure 3-5). Furthermore, both the NDVI and *f*APAR time series were more dynamic and unstable during the growing season for the younger forest canopy (Figure 3-5.) This may be due to greater heat and water stress susceptibility of the young forest, or an artifact of different light reflectance and transmittance regimes caused by the different canopy structure of the young and mature forest canopies.

The two hydrological years (2011/12 and 2012/13) measured 708 mm and 649 mm of rainfall at the field station. This was contrasted by 580 mm in 2011/12 and 730 mm in 2012/13 measured in the understory at the yTDF on the far side of the park (5km to the west), and 400 mm in 2011/12 and 450 mm in 2012/13 in the understory of the mTDF. While spatial variability in precipitation can be significant over short distances in semi-arid landscapes, the differences between the sites can also be attributed to differential rainfall interception of young and mature forest canopies. Rainfall temporal distribution was very different between the two years, with a mid-season drought in the 2012/2013 growing season. This canopy water stress led to a notable decrease in the EVI2 and an earlier onset of senescence followed by a small secondary green-up after a late season rainfall (Figure 3-3). This bimodal annual precipitation pattern was observed for several other years in these time series as well. If climate change influences precipitation patterns in this region it will be important to continue monitoring the extent and cumulative impacts of this mid-season drought on Brazilian TDFs.

In April, at the end of the rainy season, the forest progresses to a leafless state with more than 95% abscission (Madeira et al. 2009). While the plants in TDFs can withstand greater water stress than most other forest types, canopy and understory leaf wilting begins, on average, after ten to twenty days without rainfall. After two months of little to no precipitation at the end of the growing season, the greenness indices drastically decrease to about 50% of peak greenness values as leaves degrade photosynthetic pigments. During senescence, dry leaves often remain in the tree canopy and intercept sunlight, but are not photosynthetically active (confirmed by time-lapse cameras, data not shown). The onset date of greenness decrease was the same between forest age classes, but the rate of decrease was greater in the mature forest. In contrast, the onset of fAPAR decrease was earlier and progressed faster in the young forest compared to the mature forest stand. It is possible this could be caused by differences in overstory leaf wilting and leaf angle modification behaviour since water stressed trees are known to reduce sunlight interception by adjusting canopy leaf angles (Liu et al. 2003; Macdonald 2003), an element also confirmed at the MSSP via time-lapse cameras (data not shown). Since older trees typically have access to deeper water sources due to deeper roots, the mature forest canopy may not be as drought sensitive as the young forest, explaining the earlier onset of fAPAR decrease at the start of the dry season in the young forest. It's possible also that more canopy layers and greater leaf area of the mTDF reduces the degree of sensitivity in canopy greenness indices and light interception during periods of drought stress.

The fact that the greenness indices remain higher in the young forest during senescence cannot easily be explained without further in-situ investigations but may be due to the presence of drought resistance understory grasses and asynchronous understory-overstory phenology patterns in the young forest. Related work indicates that soil type and nutrient content (Cardoso et al. 2012; Valdez-Hernandez et al. 2009), and species-specific drought tolerance strategies (Borchert et al. 2002; Hasselquist et al. 2010) modified leaf phenology patterns in tropical dry forests. Alternatively, the absolute difference in forest site NDVI and EVI observed during senescence may be due to sensor viewing geometries and anisotropic reflectance changes caused by stand-age canopy structural differences, although more work is needed to verify such hypotheses.

The faster decrease in the NDVI/EVI2, compared to canopy fAPAR, in the mature forest represents an asynchrony between the spectral characteristics of the forest and the biophysical state of the canopy (Figure 3-5). So while the NDVI and EVI2 indicate the end of the photosynthetic phenology cycle, the canopy structural phenology lags behind and continues to intercept solar radiation for several weeks before complete leaf abscission. This evidence complements the findings of Guan et al. (2013) who found that remotely sensed canopy structure and function are coupled in tropical deciduous forests, but adds the caveat that this coupling is stronger during canopy development and maturity growth phases and such spectral-biophysical relationships are not as straightforward during canopy senescence in mature Tropical Dry Forests.

Canopy-Meteorology Correlation and Cross-Correlation

A temporal correlation analysis between the meteorological variables at the control weather station in the field and the canopy greenness and absorbed PAR revealed that changes in soil moisture explained more of the trend in leaf phenology than any other microclimate variable (Table 3-1). Incoming solar radiation and air temperature did not have any significant effect on canopy phenology, while relative humidity and VPD had strong correlations, but not as strong as soil water content. Rainfall had a moderate correlation strength in the first season but was much weaker in the second. The ten-day moving average rainfall had more than twice as strong a correlation with canopy phenology than daily rainfall measurements, likely due to the time lag effect between precipitation, soil penetration, and plant-water availability.

The temporal correlation strengths were very similar between young and mature forest plots but were not consistent across observation years. Rainfall was more strongly correlated with canopy leaf state in the 2011/2012 season than in the 2012/2013 season. The weaker association in the second year might be related to the less consistent rainfall pattern for that wet season. Comparing the NDVI and EVI2 greenness indices revealed that the meteorological dynamics explained more of the seasonal variability in the EVI2 than for the NDVI. The correlation analysis was also performed using the Pearson correlation equation, and in nearly all cases, the Spearman coefficient was higher indicating that the strong relationships between the TDF canopy phenology and meteorological variables are often monotonic but nonlinear. This means that whenever soil moisture increased, the measured canopy greenness also increased, but with varying rates of change or responsivity indicating that the canopy response time to moisture availability differs throughout the season, likely as a function of canopy development and plant water stress.

Our findings indicate that the senescence period canopy phenology was very strongly correlated to soil moisture (Table 3-2). This is in accordance with the findings of Reich and Borchert (1984), Borchert (1994), Murphy and Lugo (1986), and Bullock and Solis-Magallanes (1990). However, Do et al. (2005) found that deciduous tree phenology in the dry African tropics of the Sahel was controlled by deep groundwater availability (up to 31m root depths) going into the dry season, and that surface soil water content did not appear to influence leaf abscission patterns. These contrasting results may be due to species specific life history traits for these tree species in different study regions, but brings up relevant questions about deep-rooted old growth TDF trees that do rely on groundwater access for dry season sustenance. In many semi-arid agro-landscapes aquifer depletion is a serious problem; in Minas Gerais state alone more than 98% of irrigation water is sourced from ground-water (Bocanegra, 2005). If old growth TDFs rely on deep ground-water for maintaining early dry season productivity it's possible that old growth TDFs, and especially semi-evergreen tree species, may exhibit earlier onset of canopy leaf senescence, more in sync with surface soil moisture, as water tables become depleted by surrounding human agricultural activity (Hasselquist et al. 2010; Estrada-Medina et al. 2013; Fan 2015).

A cross-correlation analysis was also performed, comparing correlation strengths along time-lag increments. The main finding suggest that both young and mature tropical dry forest canopy leaf dynamics correlate best with meteorological conditions at a time lag interval between 12-15 days. This lag interval varied depending on the variable and on the temporal subset or canopy phenophase but correlation strength most notably increased for soil moisture content and rainfall. These results make sense in the context of tree physiology and biochemical and biophysical process response times, but have never before been reported in the literature for TDFs. Investigating climate-canopy response times is vital to understanding how resilient TDFs may be to climate change and the carbon exchange impacts of both severe weather and gradual shifts in climate extremes.

Understory Microclimates

Comparing Successional Stages

Several notable differences were observed between the short and long-term micrometeorological trends of the young and mature forest sites. On an annual scale, significant differences between understory heat and moisture for the two successional forest stages can be seen to evolve with canopy seasonality. Patterns of lower temperatures and higher humidity levels in the mature forest begin to emerge after the heavy rainfalls of November and December have passed, when the canopy leaf area reaches its maximum and cloudy days become less common. During January, February, and March the mean difference between understory temperature and humidity is at its greatest (Figure 3-6). February in particular shows the largest difference between young and mature forest understory microclimates. February typically has the lowest monthly rainfall during the wet season resulting in a mid-season drought month. The measured 5℃ cooler temperatures and 20% higher humidity in the mature forest makes a significant difference to plant and animal physiology during the mid-summer drought period in a tropical dry forest. At the onset of dry season these differences between forest microclimates become less pronounced as the canopy leaf area decreases. Despite this, there is greater light interception by the branches and tree trunks of the mature forest compared to the young forest, as can be seen by the amount of understory downwelling PAR in Figure 3-6.

On a diurnal scale, the range in temperature and moisture change was greater from night to day during the dry season compared to the wet season months. The greatest differences between the forest understory temperature and humidity was found during the morning hours, particularly during the wet season (Figure 3-7). During the first half of the day the temperature was, on average, higher and the humidity was lower in the young forest stand until the late afternoon and evening when these differences in micrometeorological conditions subsided. The higher temperatures and vapour deficits early in the day in the young forest are most likely due to greater canopy light penetration causing faster heating of the cool morning air in the understory. In the afternoon, the thermal mixing of near-surface air masses across the park would explain the decrease in temperature differences between the two forest sites. Very weak differences in mean air temperature and humidity were recorded between forest stands during the dry season, but the spatial variability of these micrometeorological conditions was far greater in the young forest than the mature forest. A paired t-test revealed that the mean annual midday (10:00-14:00) air temperature (T_{air}) in the understory of the mature forest was greater than the young forest by 0.8°C ($\mu T_{air} = 32.2 \pm 2.7$°C vs 31.4 ± 3.5°C, $p = 0.02$, $df = 11$). Daytime temperature maxima (T_{max}) showed even larger differences between forest stands averaging 1.3°C hotter in the young forest understory during the growing season, but typically less than 0.5°C in the dry season.

These differences may not seem large, but it is physiologically significant for plants and animals at temperatures above 30°C. Midday T_{air} varied spatially across the sensor network to a greater extent in the yTDF than the mTDF plot during the peak dry season months (Jul-Sept) when leaves were no longer present in the canopy, but more in the mTDF than the yTDF during the growing season months (Dec-Feb). The average air temperature in the young forest plot during the peak of growing season months averaged for both years was 29.6 ± 0.9°C and in the mature forest it was 27.7 ± 1.2°C. During the peak dry season months the young forest mean T_{air} was 35.0 ± 1.7°C, which was very similar to the mature TDF at 34.9 ± 0.9°C. This reversed seasonal trend between spatial variability of below-canopy T_{air}, successional stage, and canopy phenology may be caused by greater canopy structural heterogeneity in the mTDF during peak leaf area periods and higher dry season air moisture levels acting to buffer short term temperature variations.

The mature forest also had a 6.6% greater mean annual midday relative humidity (RH) than the young forest understory across the sensor network ($\mu RH = 51.4 \pm 21\%$ vs 44.8 vs $44.8 \pm 17\%$, $p < 0.001$, $df = 11$). During the peak dry season months the mean midday RH in the yTDF was 24.5 ± 3% and the VPD was 4.3 ± 0.7 kPa across the plot. This was slightly lower than in the mTDF at

27.4 ± 1.7% RH and 4.1 ± 0.6 kPa VPD. In the peak growing season months the midday RH was 63.2 ± 5.2% and VPD was 1.5 ± 0.6 kPa in the young forest, while humidity was 75.0 ± 4% with a VPD of 0.9 ± 0.6 kPa in the mature forest sensor network. Therefore, while midday air moisture was, on average, greater and evapotranspiration potential lower in the mature forest than the young forest during both seasons, the spatial variability of humidity and air saturation deficits was relatively consistent between sites. It makes sense that air moisture was less spatially variable than temperatures since heterogeneity in below-canopy light levels would drive temperature gradients more strongly than water vapour disparities. Maximum daytime VPD values were similar between plots in the dry season but were up to 1.5 kPa lower in the mature forest than the young forest.

The interaction between season, successional stage (and field control station), and understory microclimates based on the two-way analysis of variance for T_{air} and VPD is summarized in Figure 3-9. Significant differences in mean T_{air} and VPD were observed between all three sites during the leaf-on canopy state, but only between the field site and young forest understory during the leaf-off period (Figure 3-9). Significant differences in temperature and VPD were found within sites between seasons for all locations except for the temperature change in the mature TDF. This means that while air temperatures, on average, increase from the winter to summer in the open field and the young TDF, the air temperature remains just as cool during the full-leaf shaded summertime as it is during the leafless winters in the mature forest understory. This represents a very strong temperature stabilization effect throughout the year in the older successional stage TDF that is not seen in the young forest stand. Such differences between successional stage thermal seasonality may influence temperature dependent biogeochemical processes, like leaf litter decomposition and soil respiration, as well the distribution and survival of plant and animal species in secondary TDF landscapes.

Canopy Moderating Capacity

The results thus far have indicated that the broadleaf TDF canopy is quite capable of moderating understory microclimates, but the canopy moderating capacity (CMC) is not often well quantified, described over long durations, or specifically related to canopy structure. The results below describe such CMC dynamics and relate them to TDF stand age structural properties.

CMC, in reference to ambient conditions in the open field station, was found to vary both between forest sites and throughout the season, reflecting the high spatio-temporal nature of this phenomenon. The mature forest was, on average, more effective in reducing understory air temperature and moisture loss than the young forest throughout the year, but the magnitude of the CMC varied depending on the canopy state and the absolute value of the ambient measurement. The difference between field air temperature and the forest understory changed significantly throughout the year, following the same pattern seen when comparing the absolute microclimate differences between forest successional stages. The CMC demonstrated two seasonal peaks, one in January and February when canopy leaf development was complete and rainfall became less frequent, and again towards the middle or end of growing season becoming up to 3°C warmer as a daily average, and 20% less humid in the open field. The pattern of weaker CMC after a recent rainfall was further supported by an observed increase in CMC when soil moisture decreased, as long as canopy leaves were present (data not shown).

The open area to understory T_{air} and VPD difference became significantly greater when ambient air temperature and VPD increased (Figure 3-10). For example, below ambient daytime mean air temperatures of 25°C, mean canopy moderation ranged from 1-2°C, but above 25°C the below-canopy temperatures were between 2-3°C cooler. Similarly, when ambient daytime mean VPD was less than 1 kPa, mean understory VPD was up to 0.5 kPa lower, but above ambient VPD of 2 kPa, understory air had 0.5-1 kPa less humidity deficits (Figure 3-10). Furthermore, this linear effect was statistically different between the young and mature forest plots ($p<0.001$, df=145; Residual standard error: yTDFT=1.5°C, mTDFT=1.4°C, yTDFVPD=0.4, mTDFVPD=0.3). Considering this scale-dependent strength of CMC in TDFs, it may be necessary to describe vegetation CMC in reference to the absolute value of the ambient condition in future studies, to better account for temporal variations in effect strength due to changing weather conditions during short-term measurements for inter-site canopy moderation comparisons.

Daytime air temperature and VPD maximum values (T_{max} and VPD_{max}) have been shown to be important parameters for both plant and animal physiology, specifically for water balance regulation, which is vital in TDF environments (Mitler 2006). In addition, gross and net primary productivity of forests and ecosystem carbon assimilation rates are controlled by leaf stomatal conductance, which is strongly influenced by temperature and VPD thresholds (Vourlitis et al.

2002). A strong relationship was found between the below-canopy moderation of T_{max} and VPD_{max} with canopy fAPAR over time (Figure 3-11). Looking at the full two year observation period, the young forest CMC for daily maximum temperature and VPD shared a linear relationship with canopy fAPAR (GLM: R^2=0.52, p.adj<0.001, df=716, RSE=0.75°C & 0.30 kPa), while the mature forest revealed a curvilinear response in CMC with changes in canopy fAPAR over time (GLM: R^2=0.82 & 0.81, p.adj<0.001, df=716, RSE=0.76°C & 0.27 kPa). In contrast to the mean daytime values, the T_{max} and VPD_{max} were more often higher in the understory than in the field site, especially in the dry season when seasonal fAPAR was below 0.7. The higher daytime maximums in the forest are likely caused by reduced air movement in the understory and greater convective cooling in the open field. There appears to be a seasonal threshold in canopy fAPAR around 0.7 in the mature forest that was not seen in the young forest, after which the increase in moderating capacity of the canopy becomes nonlinear and significantly stronger with increasing fAPAR. These results suggest that our fAPAR measurements may begin to saturate above 70% light interception below dense older growth TDF canopies, and thus cannot explain peak rates of air temperature moderation in a simple linear fashion.

Studies regarding forest canopy-climate moderation are relatively novel in the context of climate change and forest management, but the large majority of research has been done in temperate regions in coniferous and mixed woods forest stands. Boggs and McNulty (2010) related percent canopy cover to understory air and soil temperatures in red spruce forests. Renaud et al. (2010) described the relationship between temperate forest PAR transmittance and understory microclimates in Switzerland and found site specific characteristics such as slope and soil type were important factors. Von Arx et al. (2012; 2013) found that a canopy LAI threshold of 4 in mixed temperate forest stands dictated how soil moisture regulated the dynamic behaviour of CMC strength for understory T_{max} and VPD_{max}. Vast differences in ecosystem and climatic properties exist between temperate and tropical forests; our work in TDF attempts to reduce the knowledge gap regarding CMC across forest biomes.

Lebrija-Trejos (2011) described the effect of TDF forest fallow age on below-canopy microclimate and found that understory air temperature decreased, on average, by less than 2°C from very young to old forest stands and VPD dropped by only 0.3 kPa along a 60 year TDF chronosequence. These results report similar trends to ours but show a smaller microclimatic gradient with stand age, and a lesser degree of canopy moderation in TDFs. However, their sample plots were located in very small TDF fragments of only 0.1 to 0.25 ha so edge effects may have had a significant influence on their results (Portillo-Quintero et al. 2014). In addition, their study took place in a coastal TDF in southern Mexico where mature TDF stature is typically no more than 15m in height and strong coastal winds are often present, mixing near-surface thermal air gradients (Dacre et al. 2007). The continental interior TDFs at my study site in South America can grow up to 30m in height and are not exposed to constant winds that which may explain why these results showed a greater canopy microclimate moderating effect with forest age. Furthermore, their study measured micrometeorological variables over a few days instead of continuous long-term monitoring. Our results indicate that the strength of canopy microclimate moderation in TDFs is temporally variable with the ability to change significantly over a few days, and further depends on extremes in ambient air temperature and moisture.

Climate regulation of forest stands can be difficult to quantify, and therefore is often overlooked in ecosystem valuation efforts (Hungate and Hampton 2012). The canopy moderation capacity is an important component of climate regulation services of TDFs. The values presented here in a large, undisturbed TDF should be used as an indicator of forest health and conservation effectiveness for assessments of remaining or future TDF fragmentation.

Significance

The results presented here have strong implications for current and future management of Neotropical dry forests. The long harsh dry season in TDFs is a powerful driver of young tree survival, therefore seedling establishment and tree recruitment highly depend on understory microclimates (Vieira and Scariot, 2008). As secondary TDFs become more common, it is important to understand how forest successional processes modify understory habitability for ecosystem regeneration, especially in an increasingly warmer world. Higher average temperatures and heat extremes are becoming an increasingly imminent threat to forests as the global climate changes (Jentsch and Beierkuhnlein 2008; Zhou et al. 2013). Understanding not only how TDF phenology and productivity responds to changing weather patterns and precipitation, but also how canopy moderation of heat waves can play a role in mitigating drought conditions, will help forest and land managers better adapt to any changes in TDF regeneration capacity in response to the increased anthropogenic stressors (Allen et al. 2010). After all, changes in secondary TDF functionality and resilience will directly affect the regional biogeochemistry cycles and the ecosystem services that local communities rely on.

As dry tropical forests continue to be cleared for agriculture and human settlement, their associated ecosystem services are quickly vanishing (Portillo et al. 2014). Although it is commonly understood that taller, denser forests with greater leaf area and sunlight interception will have darker, cooler, and wetter understory conditions, there is very little research that quantifies this canopy moderation effect in tropical dry forests, especially as a function of forest succession. This study, in part, helps to characterize and quantify the effect of TDF presence on climate moderation as an often overlooked ecosystem service. I argue that heat wave and drought refuge should be considered as a quantifiable ecosystem service of TDFs. Furthermore, in a warming world, CMC in the dry tropics will become increasingly important with respect to the regeneration capacity of TDFs. This evidence suggests that young TDFs could be more susceptible than later successional stage forests to increased drought severity and heat waves. With an increasing ratio of secondary to primary TDFs globally, changes in the current reforestation-deforestation balance has implications for altering tropical forest carbon sink potentials.

CONCLUSIONS

We demonstrated how meteorological conditions in a deciduous TDF influence seasonal leaf flushing and abscission. Tropical dry forests in southeastern Brazil are shown here to be highly responsive to precipitation dynamics and remaining TDF fragments may be useful bio-indicators of climate change in semi-arid regions of the Neotropics. The high-resolution near-surface remote sensing phenology time series obtained from the canopy towers and understory light sensors allowed for detailed analysis of canopy leaf expression and short-term patterns in climate-canopy interdependencies. Periods of rainy season drought, where little to no rain fell for more than two weeks caused drops in the NDVI/EVI and fAPAR signals, indicating an important effect of rainfall frequency for mid-season changes in TDF primary productivity. Slightly different temporal phenology patterns were revealed between the young and mature forest stands, primarily during leaf senescence. The young forest plot remained greener longer than the mature forest but the underlying cause was unclear. As this finding is contradictory to my expectations given higher moisture retention, higher humidity, and deeper root depths in the mature forest, further in-situ work needs to be done to explain these results. yTDF also had a slightly stronger correlation with meteorological trends during the growing season period, indicating that mTDF canopies have a greater capacity to resist above ground desiccation, likely from greater root depth and below ground water access. Such empirical data on the relationship between climate and TDF phenology is necessary to accurately parameterize resilience models for current and future TDF management.

We further examined how secondary TDF age-related structure can influence understory temperature and moisture microclimates during leaf-on and leaf-off states, relating structure to function in early stage secondary TDFs. Due to the structural and functional complexity of old growth tropical forests, secondary tropical forests may not readily return to an equivalent ecological state prior to deforestation in terms of species richness and biodiversity, but ecosystem functions based on forest structure, such as microclimate modification and diversification, can potentially recover quickly alongside tree biomass (Quesdada et al. 2009). mTDFs appear to stabilize their own microclimates during drier, hotter periods that may help support greater levels of photosynthesis and evapotranspiration. This idea is supported by the lack of significant changes in mature forest understory temperature between the dry and wet season when the young forest experienced drastic seasonal changes in understory temperature.

Our results highlight the importance of mature and old growth forest fragments in highly disturbed TDF biomes for offering refuge from seasonal and sub-seasonal drought periods. I conclude that the presence of mature and old growth TDF communities is required for maximum cooling and climate regulation in order to support the immense biodiversity of flora and fauna and the livelihoods of human populations found in these productive ecosystems. I suggest that further work needs to be done to quantify the effective forest fragment size and location to maintain temperature and moisture moderating functions at local and regional scales to better assess the role of TDFs in buffering the effects of severe drought in the Neotropics, as smaller TDF patches may be insufficient at providing such climate regulation ecosystem services.

Due to the mistiming between dropping greenness indices and constant fAPAR at the onset of canopy senescence, I also suggest a period of decoupling of canopy-climate moderation functions as detected from remotely sensed NDVI since greenness is low but sunlight interception is still high. Furthermore, given the lower moderating capacity of younger TDFs, it is reasonable to presume that seedling establishment and survival in young TDFs may be more affected by increasing heat wave and drought frequency than in older forests, possibly altering successional processes and future secondary old growth plant communities in TDFs. Such species recruitment displacement mechanisms may be a key factor in long-term forces driving ecosystem transitions of TDFs to woody savannahs as a function of climate change. TDF ecosystems are already endangered due to a long history of human disturbances but secondary dry forest management will become an even greater challenge in regions where drought severity and frequency is increasing if natural regeneration capacity is limited by harsher microclimates in young secondary forests.

ACKNOWLEDGEMENTS

We would like to thank the Inter-American Institute for Global Change Research (Collaborative Research Network 596 Program CRN3-025 funded by the USA National Science Foundation) as well as the Natural Sciences and Engineering Research Council of Canada (NSERC) for funding the majority of the project. Also the Brazilian National Council for Scientific and Technological Development (CNPq) for their funding support of our long-term field work through the University of Montes Claros, Minas Gerais, Brazil. Many thanks to everyone at the Laboratory for Evolutionary Ecology (Laboratorio de Ecologia Evolutiva, UNIMONTES), the Minas Gerais State Forestry Institute (IEF), and the extensive interdisciplinary support from all who helped keep the data loggers running (Doug Calvert – Hoskins Scientific, Daniel Costa Paula, Marco Tulio Viera, Eric Ribeiro, and the rest of the Tropi-Dry Brazil team).

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TABLE LEGENDS

TABLE 3-1. Spearman correlation coefficients for forest canopy phenology and meteorological variable time series from start of greenup to end of senescence each season. Italics indicate the only correlations that are not significant at an adjusted p-value < 0.001. All correlation coefficients above 0.75 are in bold.

TABLE 3-2. Spearman correlation coefficients and adjusted p-values for canopy green-up and senescence periods with meteorological conditions daily time series.

FIGURES LEGENDS

FIGURE 3-1. Location of Mata Seca State Park (MSSP) on the Sao Francisco River in Minas Gerais, Brazil. Forest phenology and microclimate study plots are indicated by triangular points within the park.

FIGURE 3-2. Site photos showing A. canopy and understory appearance for the young Tropical Dry Forest (TDF) site and B. hemispherical photographs looking up into the canopy of the young (above) and mature (below) forest plots.

FIGURE 3-3. Meteorological patterns from the control station paired with canopy phenology of the mature forest stand over two years of sub-hourly observations.

FIGURE 3-4. Leaf flushing of forest measured by in-situ enhanced vegetation index (EVI2) is preceded by a strong decrease in atmospheric vapour pressure deficit (VPD) Forest green-up begins 12 days after the increase in humidity levels.

FIGURE 3-5. Comparison of a) NDVI, b) EVI, and c) fAPAR phenology curves for the young and mature TDF stands. The mature forest has a higher mid-growing season NDVI but lower EVI and a consistently higher and more stable level of canopy light interception than the young TDF. The young forest retains a higher greenness index during senescence phase but tends to decrease in the fAPAR sooner.

FIGURE 3-6. Spatial and temporal variability of TDF understory air temperature, relative humidity, and canopy transmitted photosynthetic active radiation (PAR) across the long-term wireless sensor network in young and mature forest plots from 2011 to 2013. Error bars are the standard deviation between the 12 sensor locations describing spatial variability of microclimates in the 2,500 m^2 plots. Observations were filtered for midday values between 10:00 and 14:00. Higher temperatures, lower humidity, and higher light levels were seen in the younger TDF, becoming more pronounced during canopy leaf presence from November to May.

FIGURE 3-7. Diurnal understory microclimate dynamics across wireless sensor networks comparing young and mature TDF plots. Dry season data spans from July to September, wet season data spans from January to March averaged for the 2011/2012 and 2012/2013 seasons. Error bars are spatial standard deviation within the plot.

FIGURE 3-8. A comparison of daytime mean air temperature, relative humidity, and vapour pressure deficit for the open field, the young forest and the mature secondary tropical dry forest during the peak months of the leaf-off dry season (Jul-Sept) and leaf-on rainy season (Dec-Feb).

Higher mean and variance in temperature and humidity levels are observed in the younger forest compared to the mature stand during the rainy, leaf-on season.

FIGURE 3-9. Interaction plots between season (i.e. canopy leaf state), site (field, young TDF, and mature TDF), understory air temperature, and vapour pressure deficit. The left side plots compare between sites but within the same season, the right side plots compare within sites but between seasons. All significant interactions are denoted by an asterisk beside the interaction lines (ANOVA, p.adj.<0.001, df =709).

FIGURE 3-10. Canopy Moderating Capacity (CMC) for daytime understory a) air temperature and b) vapour pressure deficit (VPD) increases with temperature extremes. This effect is 30% stronger in mature forests than young forests, on average, and up to twice as strong when moisture levels were lowest during the growing season. * ($p<0.001$, df=145; Residual standard error: yTDFT=1.5°C, mTDFT=1.4°C, yTDFVPD=0.4, mTDFVPD=0.3).

FIGURE 3-11. Canopy moderating capacity for daytime maximum air temperature (above) and vapour pressure deficit (below) as a function of temporal changes in canopy fraction of absorbed photosynthetic active radiation (fAPAR) for young and mature secondary TDF sites. Mature TDF shows a stronger moderating effect and a nonlinear increase in climate moderation at high fAPAR levels. CMC values above zero indicate desirable microclimate moderation relative to the open area control measurements. All regressions meet model assumptions and are significant at $p<0.001$.

FIGURE 3-A1. Phenophase heat and moisture buffering capacity of young and mature TDFs. For the 2011/12 and 2012/13 growing season the temperature and VPD difference between forest understory and a nearby open field were compared. Positive values (y-axis) indicate the degree of cooling/dampening while negative values indicate heating/drying effects of the forest. GLMs were run to test that the slope of the difference was non-zero indicating a change in the buffering capacity for the duration of the phenophase. X-axis represents consecutive days of the phenophase. Mature TDF stand demonstrates a greater ability to buffer heat and moisture than the younger stand depending on the canopy leaf state and atmospheric temperature and moisture extremes. Unexpectedly, the buffering capacity of the forest was greater during leaf maturity when soils were driest and temperatures were highest.

(TABLE 3-1)

2012/2013	*iSR*	*Rain*	*10d-Rain*	*SWC*	*AT*	*RH*	*VPD*
mTDF EVI2	0.17	0.35	0.65	**0.83**	0.17	0.73	-0.59
yTDF EVI2	*0.11*	0.29	0.59	**0.85**	*0.08*	**0.78**	-0.65
mTDF FAPAR	*0.16*	0.23	0.51	**0.83**	*0.11*	**0.78**	-0.65
yTDF FAPAR	0.18*	0.26	0.55	**0.84**	0.13	**0.77**	-0.64
2013/2014	*iSR*	*Rain*	*10d-Rain*	*SWC*	*AT*	*RH*	*VPD*
mTDF EVI2	0.16	*0.12*	0.36	**0.81**	0.30	0.69	-0.48
yTDF EVI2	*0.06*	*0.10*	0.32	**0.84**	*0.13*	**0.77**	-0.61
mTDF FAPAR	*0.10*	*0.08*	0.27	**0.80**	*0.15*	0.72	-0.56
yTDF FAPAR	*0.13*	*0.08*	0.32	**0.81**	*0.15*	0.70	-0.54

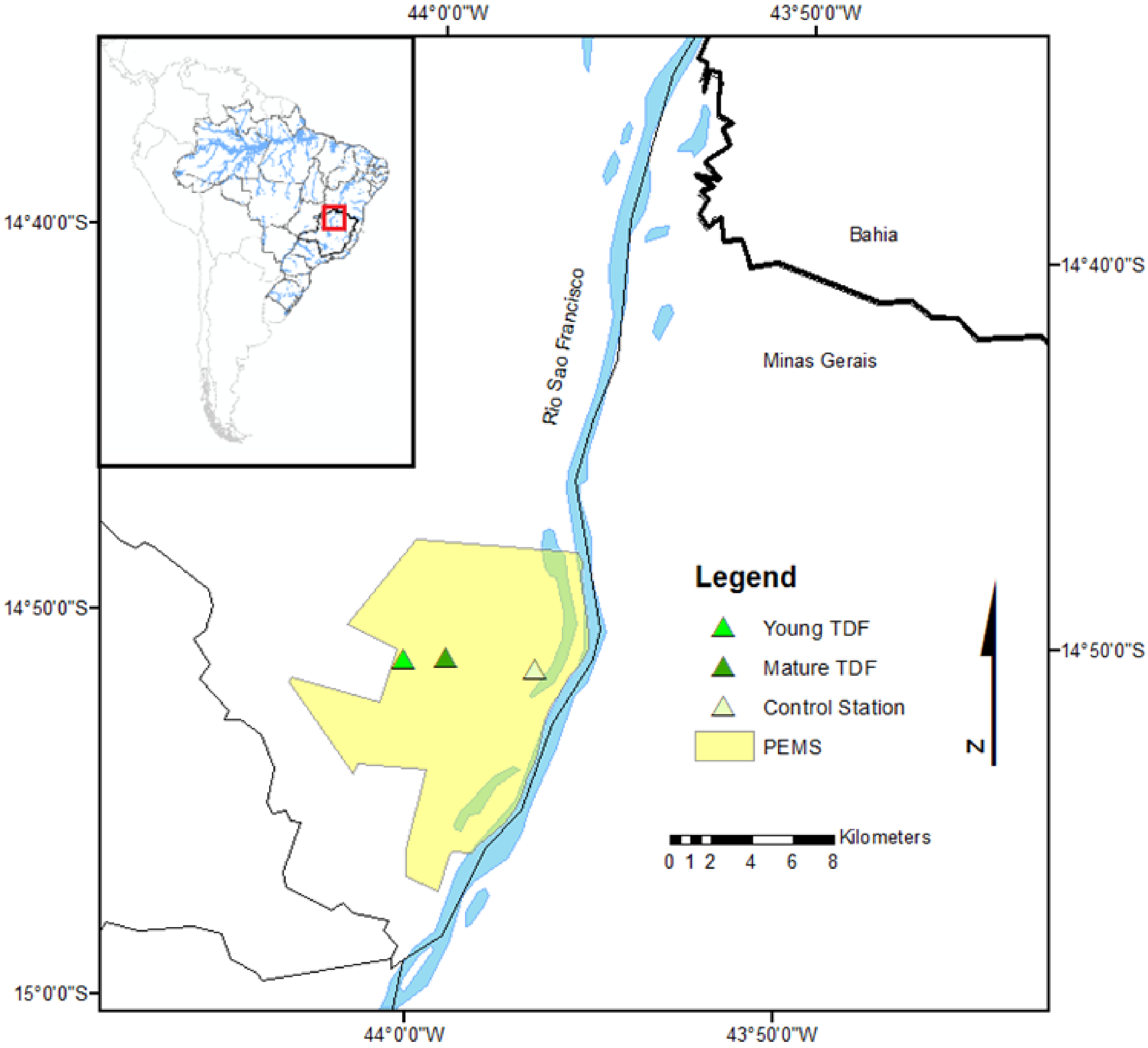
All variables are daily averages except Rain, which is daily sum precipitation, and 10d-Rain which is the 10 day moving average Rain. iSR = incoming solar radiation, SWC = volumetric soil water content, RH = relative humidity, VPD = vapour pressure deficit. mTDF = mature forest, yTDF = young forest. EVI2= two-band enhanced vegetation index, fAPAR = fraction of absorbed photosynthetically active radiation.

(TABLE 3-2)

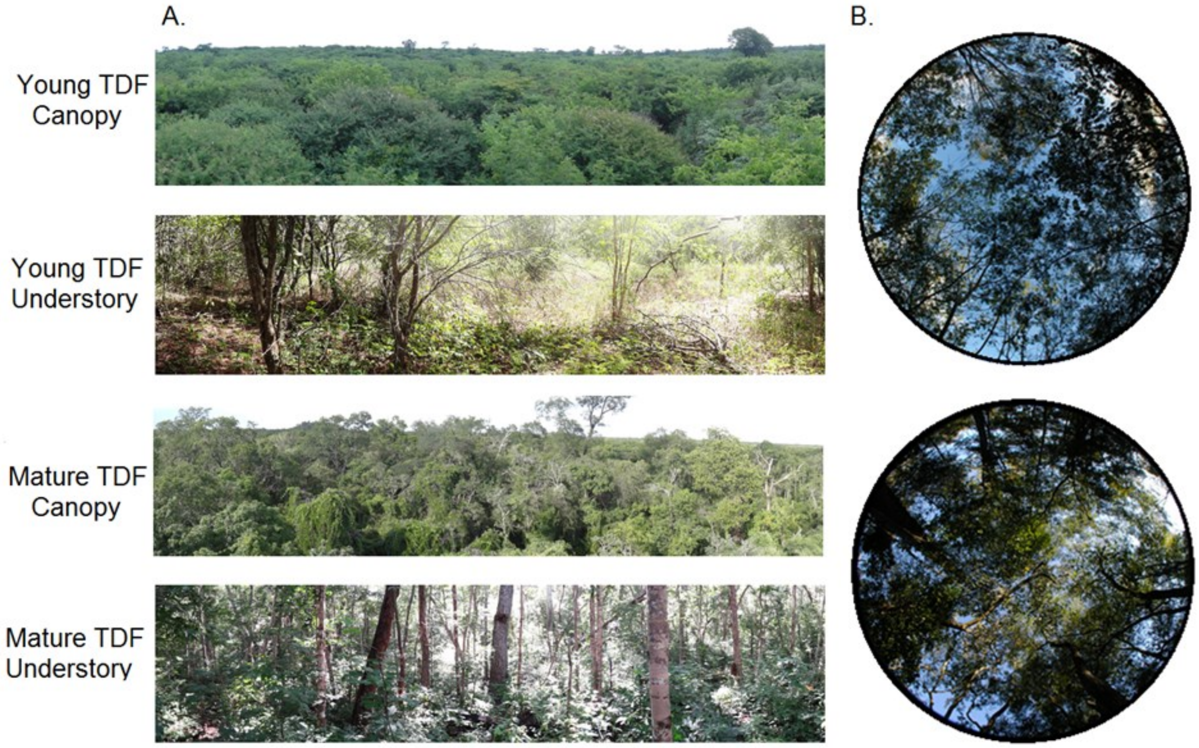
2011														
GREENUP	**iSR**	**p.adj**	**RAIN**	**p.adj**	**10d-Rain**	**p.adj**	**SWC**	**p.adj**	**AT**	**p.adj**	**RH**	**p.adj**	**VPD**	**p.adj**
YF NDVI	0.10	1.00	0.09	1.00	0.14	1.00	0.26	1.00	-0.37	0.64	0.53	0.02	-0.48	0.05
YF EVI2	0.10	1.00	0.09	1.00	0.14	1.00	0.26	1.00	-0.38	0.59	0.53	0.01	-0.49	0.04
YF FAPAR	0.12	1.00	0.10	1.00	0.13	1.00	0.30	1.00	-0.41	0.29	0.53	0.01	-0.50	0.04
MF NDVI	0.10	1.00	0.09	1.00	0.14	1.00	0.26	1.00	-0.37	0.64	0.53	0.02	-0.48	0.05
MF EVI2	0.12	1.00	0.06	1.00	0.13	1.00	0.26	1.00	-0.39	0.48	0.53	0.02	-0.49	0.04
MF FAPAR	0.10	1.00	0.09	1.00	0.14	1.00	0.26	1.00	-0.37	0.64	0.53	0.02	-0.48	0.05
2012														
SENESCENCE	**iSR**	**p.adj**	**RAIN**	**p.adj**	**10d-Rain**	**p.adj**	**SWC**	**p.adj**	**AT**	**p.adj**	**RH**	**p.adj**	**VPD**	**p.adj**
YF NDVI	0.71	<.0001	0.11	1.00	0.23	1.00	0.97	<.0001	0.54	<.0001	0.21	1.00	-0.02	1.00
YF EVI2	0.75	<.0001	0.08	1.00	0.19	1.00	0.98	<.0001	0.56	<.0001	0.23	1.00	-0.05	1.00
YF FAPAR	0.68	<.0001	0.07	1.00	0.23	1.00	0.90	<.0001	0.54	<.0001	0.23	1.00	-0.05	1.00
MF NDVI	0.75	<.0001	0.08	1.00	0.19	1.00	0.98	<.0001	0.56	<.0001	0.23	1.00	-0.05	1.00
MF EVI2	0.75	<.0001	0.08	1.00	0.19	1.00	0.98	<.0001	0.56	<.0001	0.23	1.00	-0.05	1.00
MF FAPAR	0.74	<.0001	0.09	1.00	0.16	1.00	0.98	<.0001	0.56	<.0001	0.23	1.00	-0.04	1.00
2012														
GREENUP	**iSR**	**p.adj**	**RAIN**	**p.adj**	**10d-Rain**	**p.adj**	**SWC**	**p.adj**	**AT**	**p.adj**	**RH**	**p.adj**	**VPD**	**p.adj**
YF NDVI	0.23	1.00	-0.02	1.00	0.39	0.41	0.69	<.0001	-0.18	1.00	0.15	1.00	-0.16	1.00
YF EVI2	0.16	1.00	0.07	1.00	0.40	0.32	0.67	<.0001	-0.24	1.00	0.24	1.00	-0.24	1.00
YF FAPAR	0.33	1.00	-0.12	1.00	0.30	1.00	0.62	<.001	-0.14	1.00	0.06	1.00	-0.07	1.00
MF NDVI	0.35	0.81	-0.13	1.00	0.22	1.00	0.52	0.02	-0.11	1.00	0.06	1.00	-0.06	1.00
MF EVI2	0.35	0.81	-0.13	1.00	0.22	1.00	0.52	0.02	-0.11	1.00	0.06	1.00	-0.06	1.00
MF FAPAR	0.35	0.81	-0.13	1.00	0.22	1.00	0.52	0.02	-0.11	1.00	0.06	1.00	-0.06	1.00
2013														
SENESCENCE	**iSR**	**p.adj**	**RAIN**	**p.adj**	**10d-Rain**	**p.adj**	**SWC**	**p.adj**	**AT**	**p.adj**	**RH**	**p.adj**	**VPD**	**p.adj**
YF NDVI	0.56	0.00	0.26	1.00	0.29	1.00	1.00	<.0001	-0.32	0.81	0.38	0.26	-0.40	0.18
YF EVI2	0.56	0.00	0.26	1.00	0.29	1.00	1.00	<.0001	-0.32	0.81	0.38	0.26	-0.40	0.18
YF FAPAR	0.50	0.01	0.21	1.00	0.38	0.27	0.97	<.0001	-0.33	0.73	0.39	0.22	-0.42	0.11
MF NDVI	0.56	0.00	0.26	1.00	0.29	1.00	1.00	<.0001	-0.32	0.81	0.38	0.26	-0.40	0.18
MF EVI2	0.56	0.00	0.26	1.00	0.29	1.00	1.00	<.0001	-0.32	0.81	0.38	0.26	-0.40	0.18
MF FAPAR	0.56	0.00	0.26	1.00	0.29	1.00	1.00	<.0001	-0.32	0.81	0.38	0.26	-0.40	0.18

iSR = incident solar radiation, RAIN = daily sum rainfall, 10d-Rain = 10-day moving average RAIN, SWC = volumetric soil water content, AT = air temperature, RH = relative humidity, VPD = vapor pressure deficit.

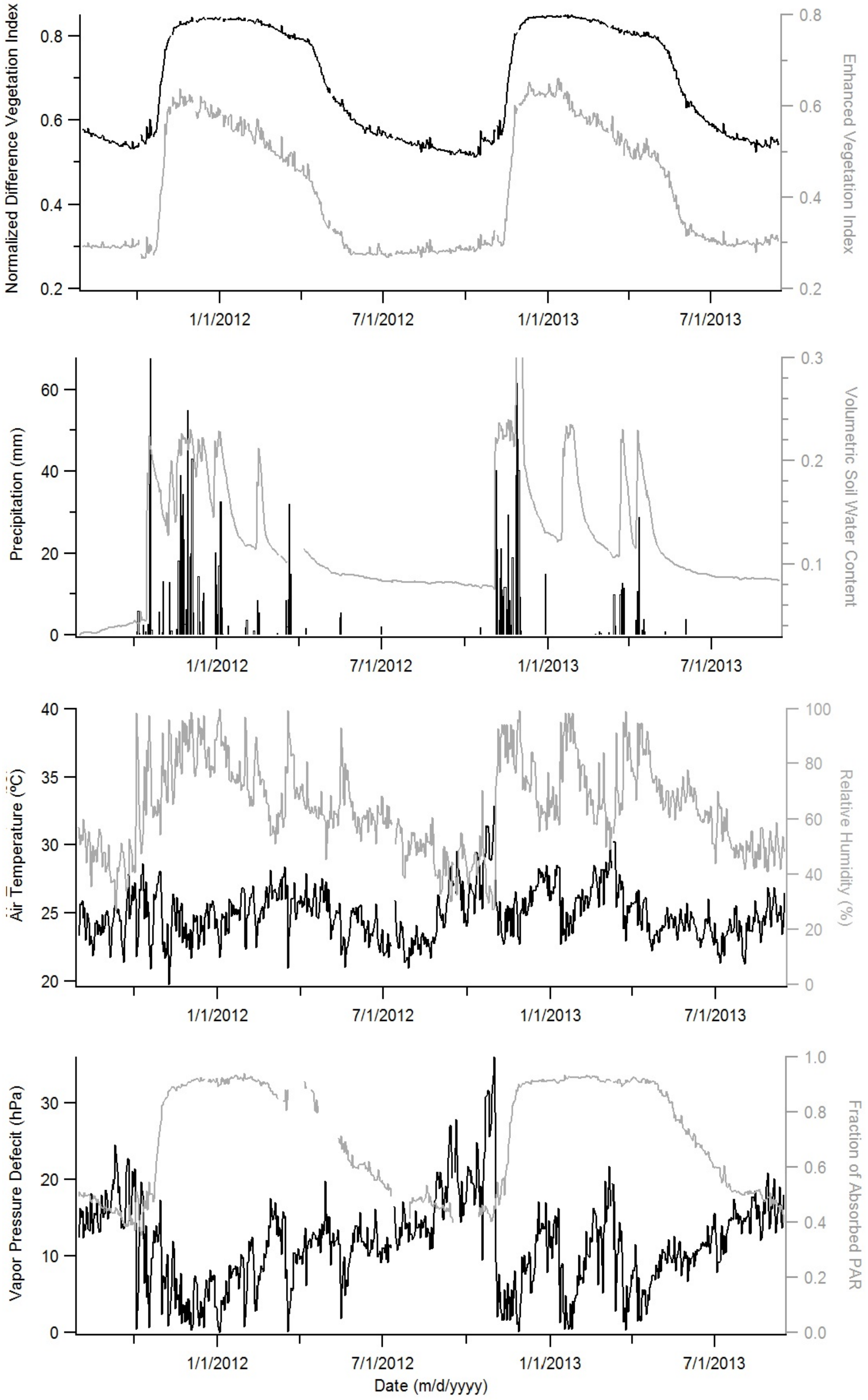
(FIGURE 3-1)


44°0'0"W
43°50'0"W
14°40'0"S
14°50'0"S
15°0'0"S
Bahia
Minas Gerais
Rio Sao Francisco
Legend
Young TDF
Mature TDF
Control Station
PEMS
N
Kilometers
0 1 2 4 6 8

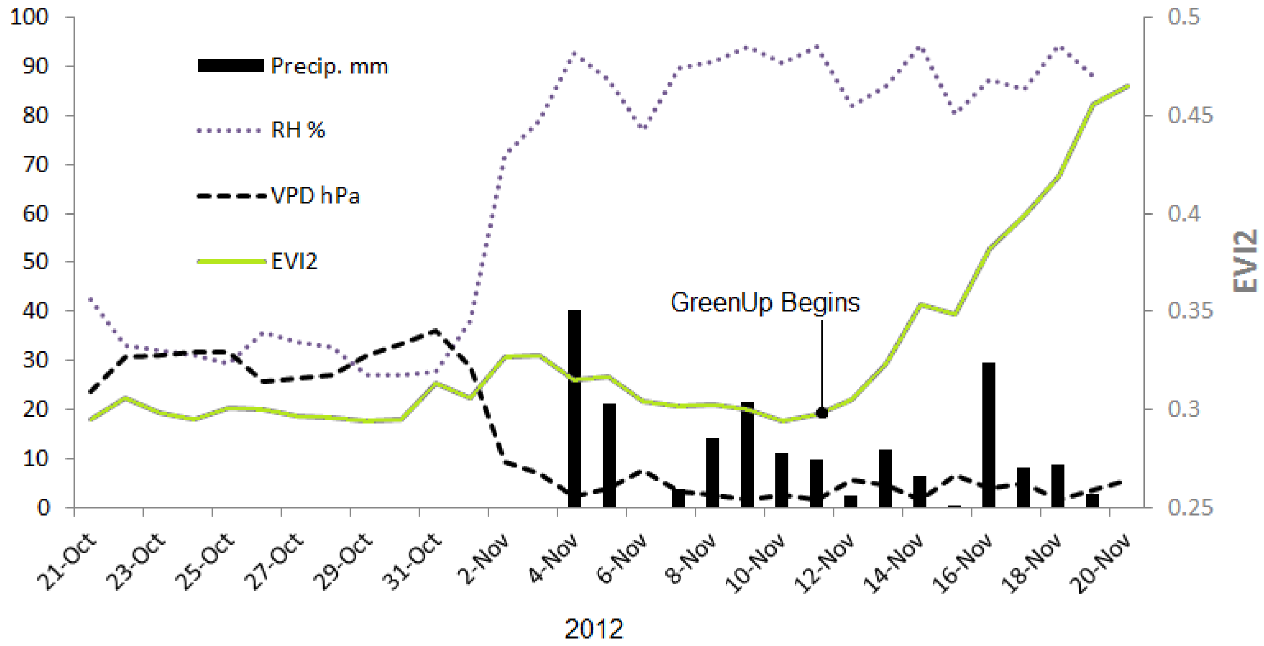
(FIGURE 3-2)


A.
B.
Young TDF Canopy
Young TDF Understory
Mature TDF Canopy
Mature TDF Understory

(FIGURE 3-3)

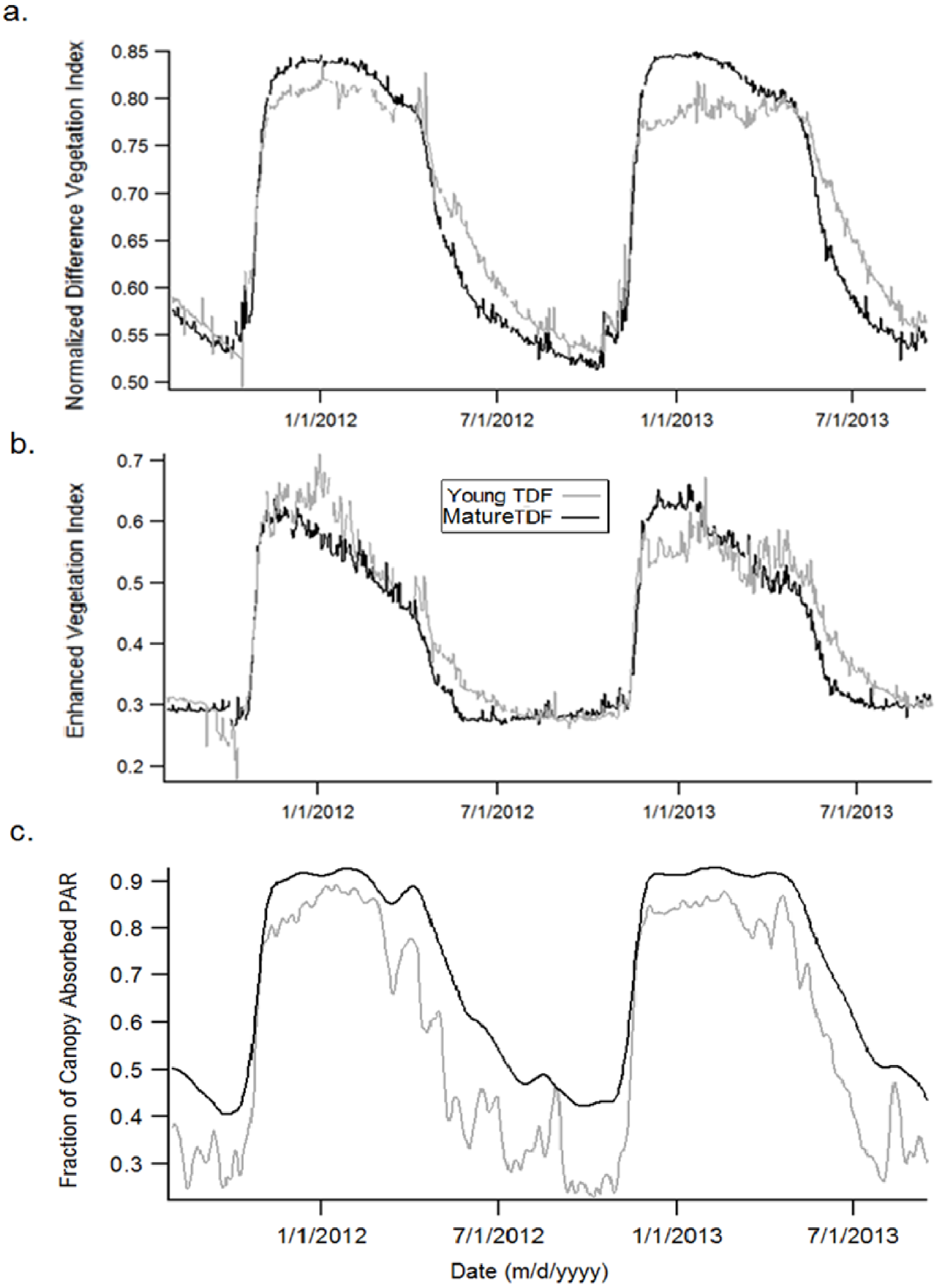

Normalized Difference Vegetation Index
0.2
0.4
0.6
0.8
Enhanced Vegetation Index
0.2
0.4
0.6
0.8
1/1/2012
7/1/2012
1/1/2013
7/1/2013
Precipitation (mm)
0
20
40
60
Volumetric Soil Water Content
0.1
0.2
0.3
1/1/2012
7/1/2012
1/1/2013
7/1/2013
Air Temperature (ºC)
20
25
30
35
40
Relative Humidity (%)
0
20
40
60
80
100
1/1/2012
7/1/2012
1/1/2013
7/1/2013
Vapor Pressure Defecit (hPa)
0
10
20
30
Fraction of Absorbed PAR
0.0
0.2
0.4
0.6
0.8
1.0
1/1/2012
7/1/2012
1/1/2013
7/1/2013
Date (m/d/yyyy)

(FIGURE 3-4)

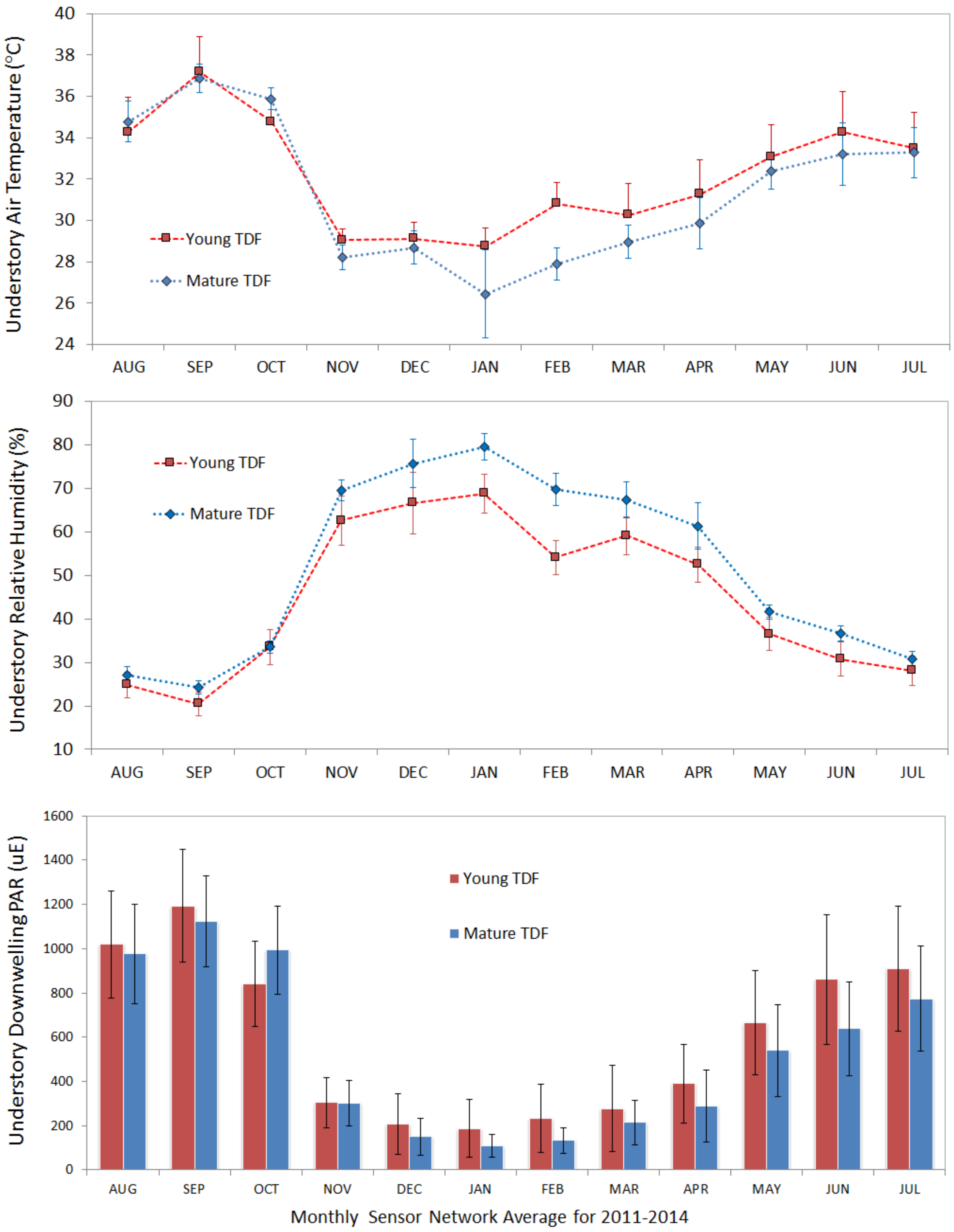


100
90
80
70
60
50
40
30
20
10
0
Precip. mm
RH %
VPD hPa
EVI2
GreenUp Begins
0.5
0.45
0.4
0.35
0.3
0.25
EVI2
21-Oct
23-Oct
25-Oct
27-Oct
29-Oct
31-Oct
2-Nov
4-Nov
6-Nov
8-Nov
10-Nov
12-Nov
14-Nov
16-Nov
18-Nov
20-Nov
2012

(FIGURE 3-5)

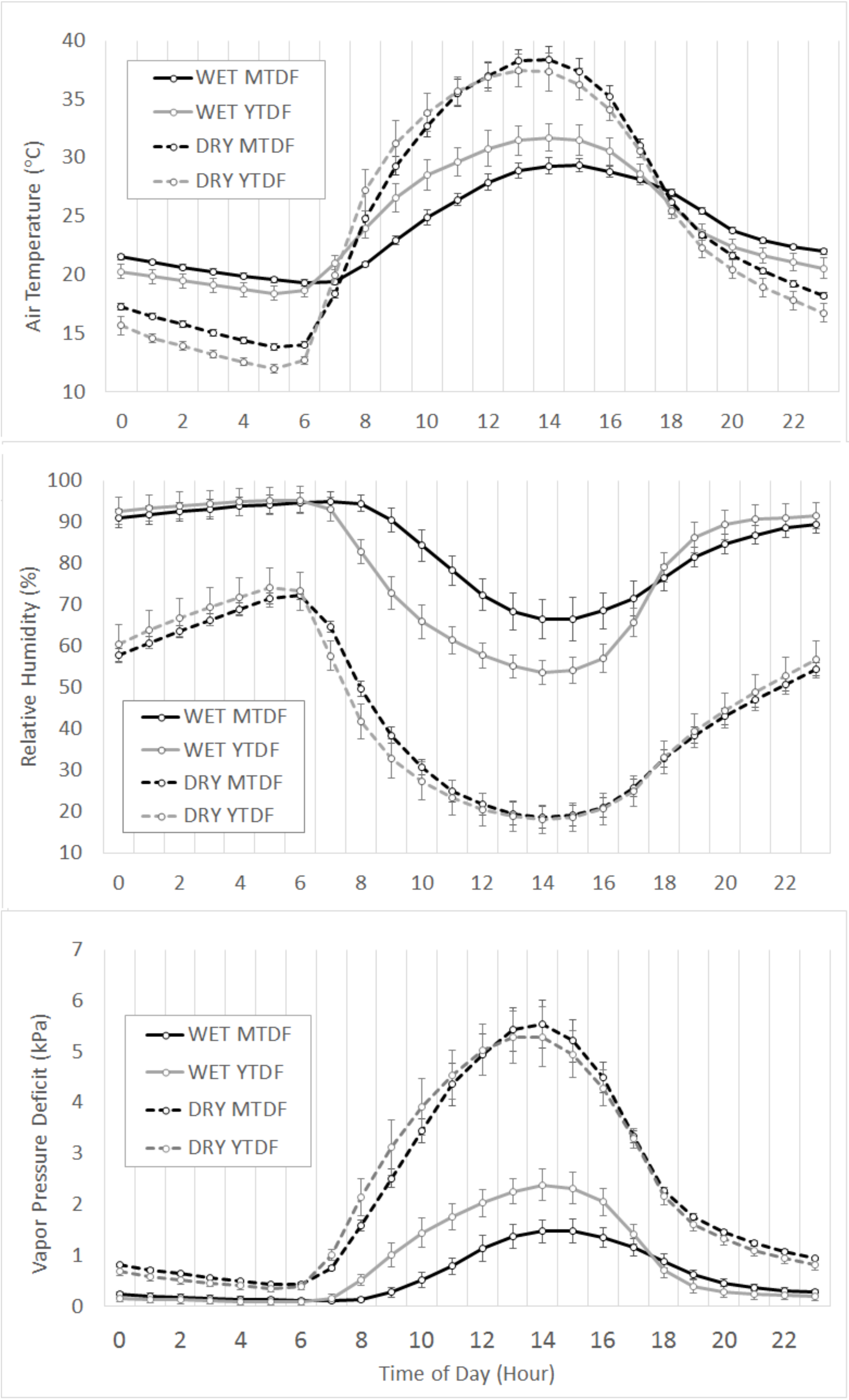

a.
Normalized Difference Vegetation Index
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
1/1/2012
7/1/2012
1/1/2013
7/1/2013
b.
Enhanced Vegetation Index
0.7
0.6
0.5
0.4
0.3
0.2
Young TDF
MatureTDF
1/1/2012
7/1/2012
1/1/2013
7/1/2013
c.
Fraction of Canopy Absorbed PAR
0.9
0.8
0.7
0.6
0.5
0.4
0.3
1/1/2012
7/1/2012
1/1/2013
7/1/2013
Date (m/d/yyyy)

(FIGURE 3-6)



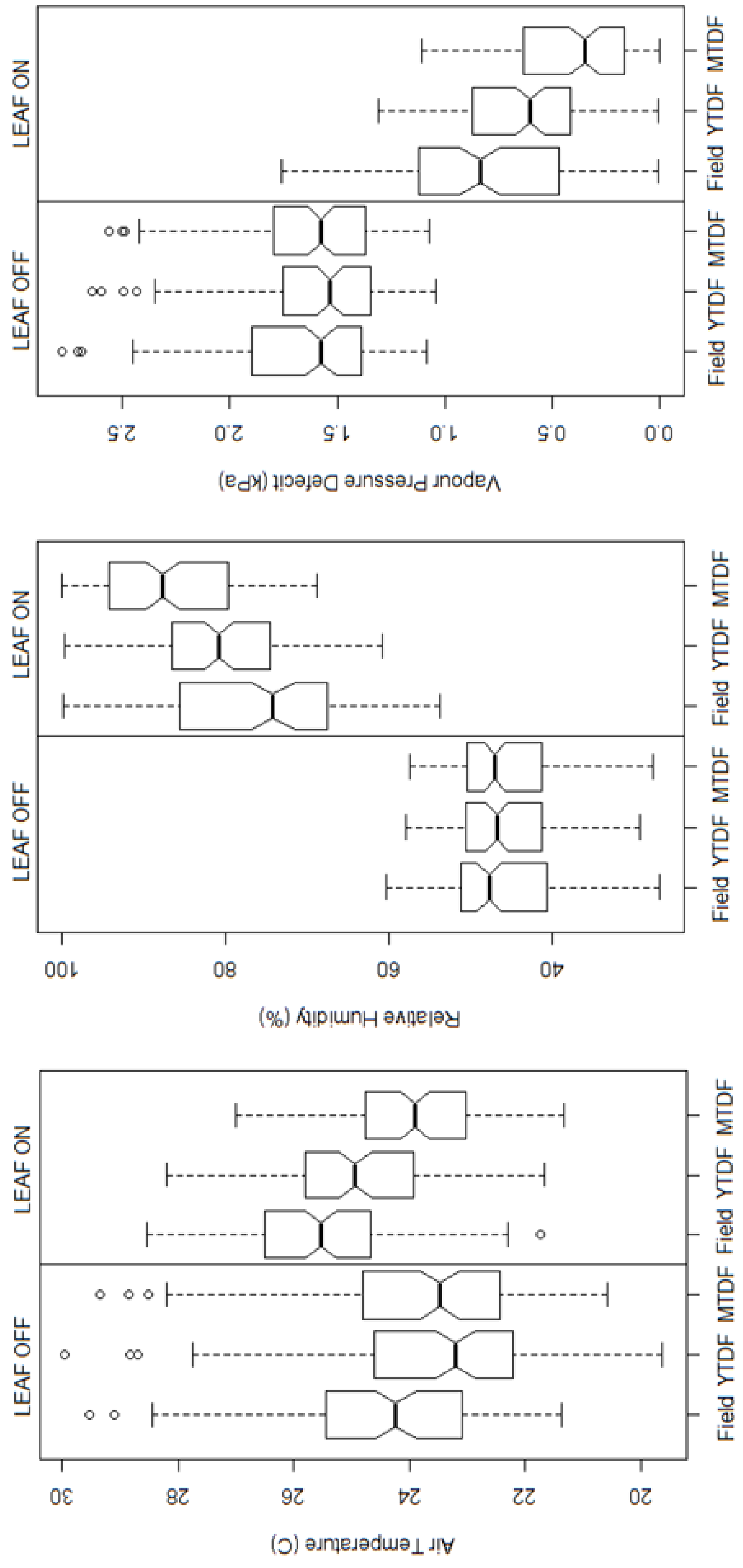
Understory Air Temperature (°C)
40
38
36
34
32
30
28
26
24
Young TDF
Mature TDF
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
Understory Relative Humidity (%)
90
80
70
60
50
40
30
20
10
Young TDF
Mature TDF
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
Understory Downwelling PAR (uE)
1600
1400
1200
1000
800
600
400
200
0
Young TDF
Mature TDF
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
Monthly Sensor Network Average for 2011-2014

(FIGURE 3-7)



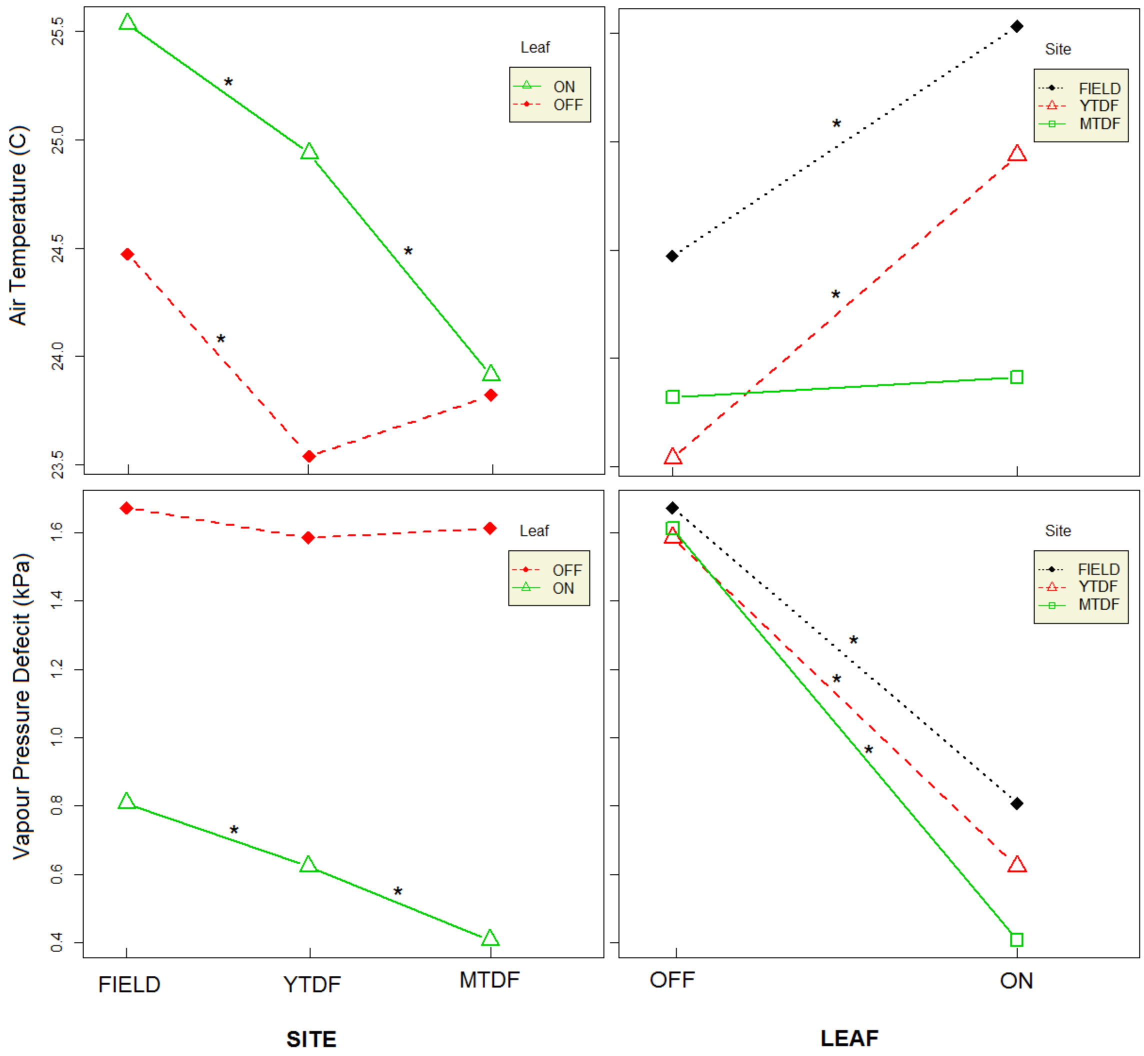
Air Temperature (°C)
40
35
30
25
20
15
10
WET MTDF
WET YTDF
DRY MTDF
DRY YTDF
0
2
4
6
8
10
12
14
16
18
20
22
Relative Humidity (%)
100
90
80
70
60
50
40
30
20
10
WET MTDF
WET YTDF
DRY MTDF
DRY YTDF
0
2
4
6
8
10
12
14
16
18
20
22
Vapor Pressure Deficit (kPa)
7
6
5
4
3
2
1
0
WET MTDF
WET YTDF
DRY MTDF
DRY YTDF
0
2
4
6
8
10
12
14
16
18
20
22
Time of Day (Hour)

(FIGURE 3-8)



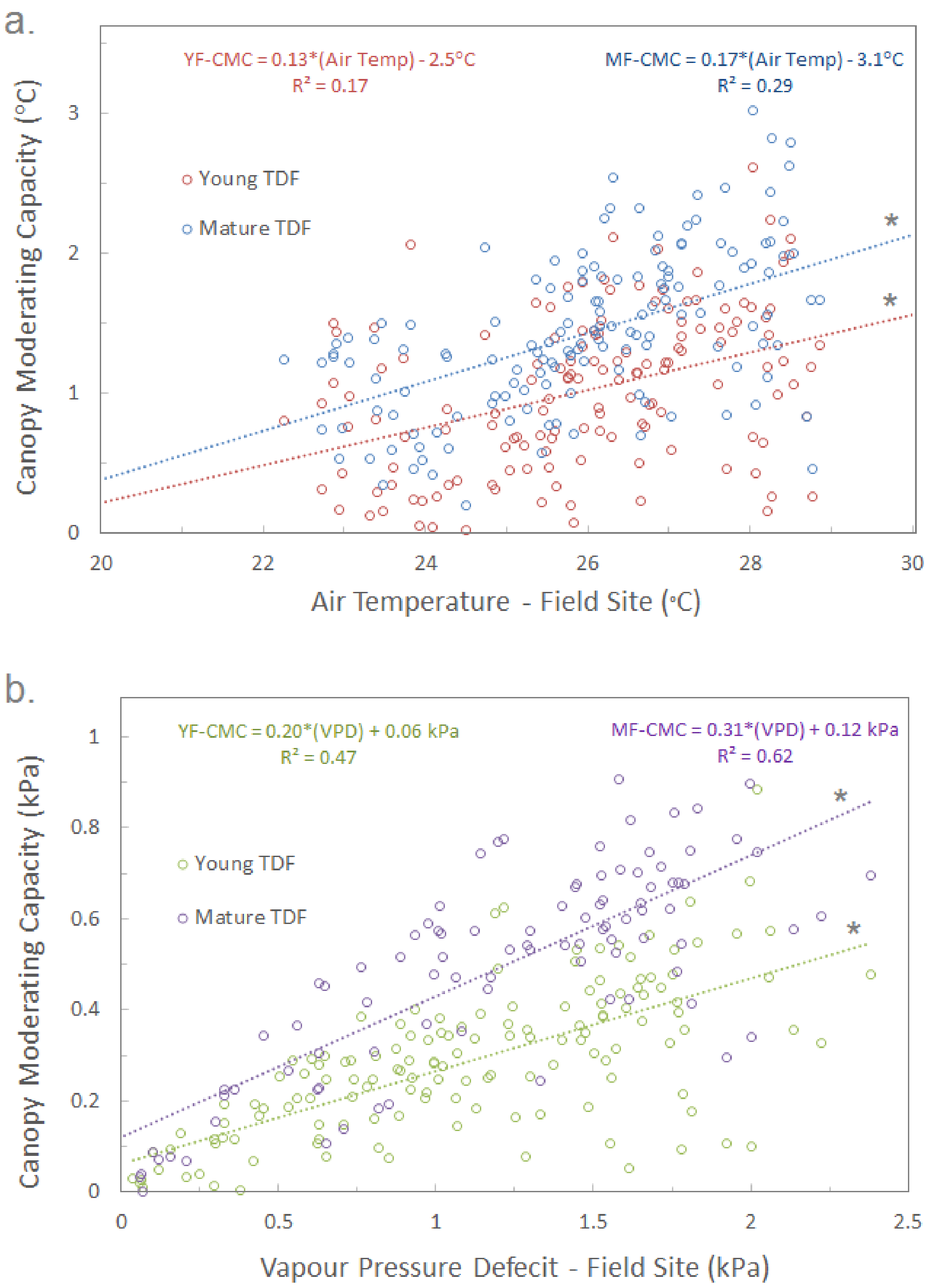
LEAF OFF
LEAF ON
Field
YTDF
MTDF
Vapour Pressure Deficit (kPa)
0.0
0.5
1.0
1.5
2.0
2.5
Relative Humidity (%)
40
60
80
100
Air Temperature (C)
20
22
24
26
28
30

(FIGURE 3-9)

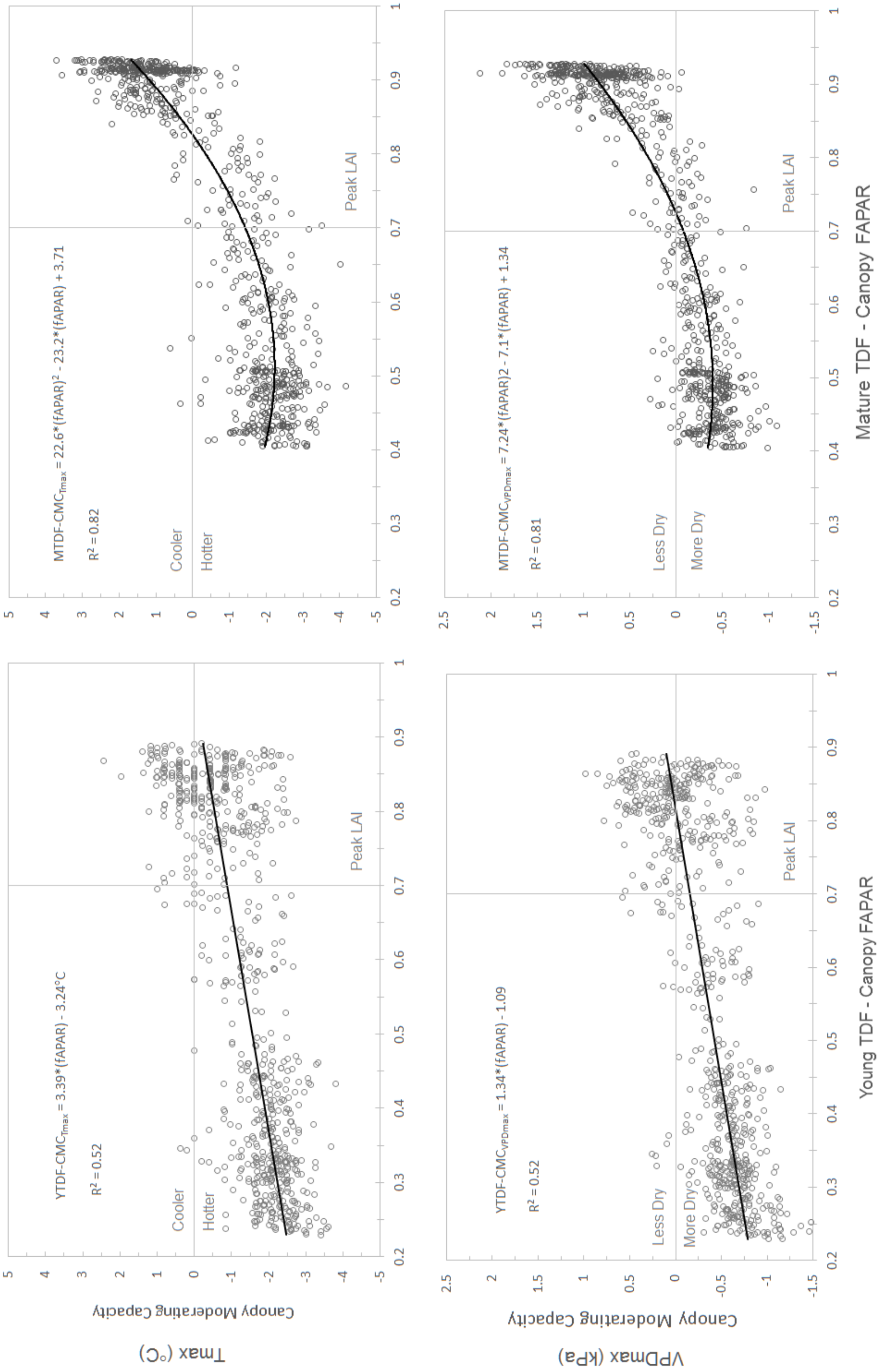


Air Temperature (C)
25.5
25.0
24.5
24.0
23.5
Leaf
ON
OFF
Site
FIELD
YTDF
MTDF
Vapour Pressure Defecit (kPa)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
Leaf
OFF
ON
Site
FIELD
YTDF
MTDF
FIELD
YTDF
MTDF
OFF
ON
SITE
LEAF

(FIGURE 3-10)

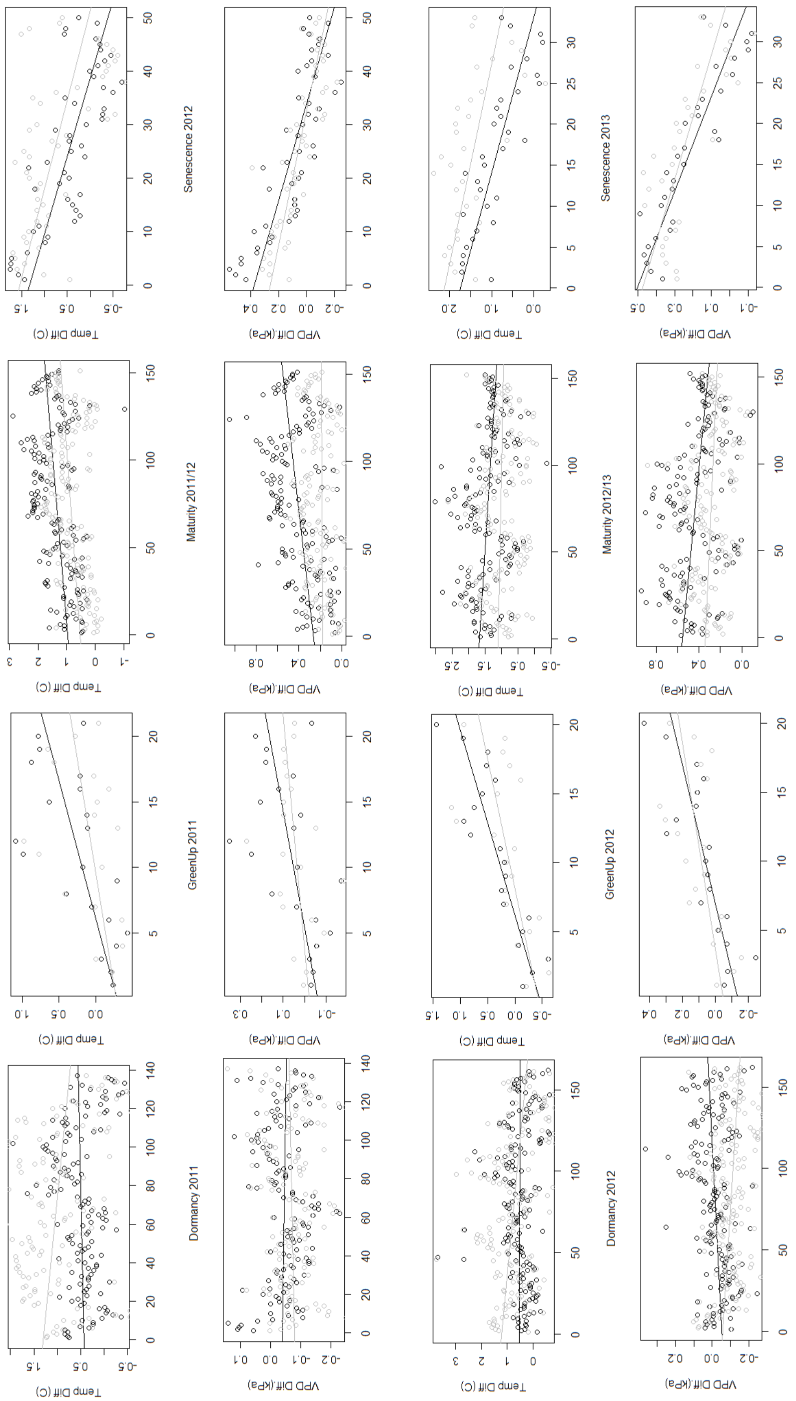

a.
YF-CMC = 0.13*(Air Temp) - 2.5°C
R² = 0.17
MF-CMC = 0.17*(Air Temp) - 3.1°C
R² = 0.29
Young TDF
Mature TDF
*
*
Canopy Moderating Capacity (°C)
0
1
2
3
20
22
24
26
28
30
Air Temperature - Field Site (°C)
b.
YF-CMC = 0.20*(VPD) + 0.06 kPa
R² = 0.47
MF-CMC = 0.31*(VPD) + 0.12 kPa
R² = 0.62
Young TDF
Mature TDF
*
*
Canopy Moderating Capacity (kPa)
0
0.2
0.4
0.6
0.8
1
0
0.5
1
1.5
2
2.5
Vapour Pressure Defecit - Field Site (kPa)

(FIGURE 3-11)


MTDF-CMC$_{Tmax}$ = 22.6*(fAPAR)^2 - 23.2*(fAPAR) + 3.71
R² = 0.82
Cooler
Hotter
Peak LAI
MTDF-CMC$_{VPDmax}$ = 7.24*(fAPAR)2 - 7.1*(fAPAR) + 1.34
R² = 0.81
Less Dry
More Dry
Peak LAI
Mature TDF - Canopy FAPAR
YTDF-CMC$_{Tmax}$ = 3.39*(fAPAR) - 3.24°C
R² = 0.52
Cooler
Hotter
Peak LAI
YTDF-CMC$_{VPDmax}$ = 1.34*(fAPAR) - 1.09
R² = 0.52
Less Dry
More Dry
Peak LAI
Young TDF - Canopy FAPAR
Tmax (°C)
Canopy Moderating Capacity
VPDmax (kPa)
Canopy Moderating Capacity
5
4
3
2
1
0
-1
-2
-3
-4
-5
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

APPENDIX

(FIGURE 3-A1)



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CHAPTER 4

COMPARING MODIS AND HYPERTEMPORAL NEAR-SURFACE VEGETATION INDICES FOR MONITORING TROPICAL DRY FOREST PHENOLOGY ALONG A SUCCESSIONAL GRADIENT

ABSTRACT

Tropical Dry Forests (TDF) present very strong seasonal greenness signals ideal for tracking phenology and primary productivity using remote sensing techniques. The tightly synchronized relationship that these ecosystems have with water availability offers a valuable natural experiment for observing the complex interactions between the atmosphere and the biosphere in the tropics. To investigate how well the MODIS vegetation indices (NDVI and EVI) represent the phenology of different successional stages of naturally regenerating TDF, within a largely conserved forest fragment in the semi-arid southeast of Brazil, several canopy towers with radiometric sensors were installed to produce high temporal resolution near-surface vegetation greenness indices. Direct comparison of several years of tower-based measurements with a combined Aqua/Terra 8-day satellite product showed similar broad temporal trends but MODIS often suffered from cloud contamination during the onset of the growing season and occasionally during the peak growing season. The strength of the in-situ and MODIS linear relationship was greater for NDVI than for EVI across sites but varied with forest stand age. Furthermore, the onset dates and duration of canopy development phases for three years of in-situ monitoring are described. A seasonality analysis revealed large discrepancies between tower radiometric and MODIS phenology transitions dates, with up to five weeks overestimation in growing season length from satellite. These results indicate that 8 and 16 day MODIS satellite vegetation monitoring products are suitable for tracking general patterns of TDF phenology in this region but are not temporally sufficient to characterize inter-annual differences in phenology phase onset dates, or changes in productivity due to mid-season droughts. Such rapid transitions in canopy greenness are vital indicators of climate change sensitivity of these already endangered forest ecosystems and should be further monitored using both near-surface and satellite sensing approaches.

INTRODUCTION

Tropical Dry Forest Phenology

Land surface vegetation phenology, or the seasonal cycles of plant growth and senescence, is a fundamental process that perpetuates biogeochemical cycling between the Earth's biosphere, geosphere, and the atmosphere. Changes in phenology act as important indicators of ecosystem function and integrity with respect to global change (Menzel, 2002). While the leaf phenology of temperate regions is well studied and known to be changing (Buitenwerf et al., 2015), the seasonality of tropical deciduous vegetation, specifically in the semi-arid Tropical Dry Forests (TDFs), is underrepresented in the scientific literature and multi-year growth dynamics are often poorly understood (Sanchez-Azofeifa et al., 2005). The absence of significant monitoring efforts for TDF leaf phenology is contrasted by the important role these tropical forest ecosystems play in moderating the exchange of carbon, water, and energy between the land surface and the atmosphere (Navar et al., 2010; Singh & Singh, 1991; Meister et al., 2012). Furthermore, the lack of detailed empirical observations on TDF phenology makes modelling their growth and productivity dynamics a serious challenge for climate-biosphere studies (Medvidgy et al., 2010; Rowland et al., 2015).

TDFs are defined by having at least 50% drought-deciduous tree presence with a mean annual temperature greater than 25°C and experiencing between 700 and 2000 mm of annual precipitation, where less than 100 mm falls per month for at least 3 months each year (Sanchez-Azofeifa et al., 2005). TDFs make up nearly half of the forested land in the tropics, with the largest remaining extent found in Latin America (Portillo-Quintero and Sanchez-Azofeifa, 2010). Only recently have TDFs begun to be recognized beyond some national governments for their wealth of unique biodiversity and wide range of ecosystem services they offer (Maass et al., 2004). Historically, TDFs in Central and South America have experienced higher rates of human colonization and extensive land cover change due to their fertile soils for agriculture and favorable climate over tropical moist and wet forests (Quesada et al, 2009). Remaining TDFs in the Neotropics are typically highly fragmented, chronically degraded, and generally suffer from insufficient conservation efforts (Sanchez-Azofeifa et al, 2003; 2005, Portillo-Quintero & Sanchez-Azofeifa, 2010). With exposure to high solar irradiance and mean evapotranspiration demands often in excess of precipitation, the TDF canopy becomes dormant for several months each year in order to conserve water during the long annual droughts. Deciduous trees dominate the TDF landscape due to the adaptive advantages of seasonal foliage loss and regrowth, a water stress avoidance strategy which can only be afforded by nutrient rich soils (Ishida et al, 2006). This drastic seasonal change in landscape leaf surface area drives local and regional patterns in atmospheric moisture, heat, and carbon dioxide dynamics through landscape scale processes of photosynthesis, evapotranspiration, and respiration.

The phenology of Tropical Dry Forests are known to be very strongly dependent on patterns of soil and atmospheric water availability (Reich and Borchert, 1984) and thus the length of the growing season and extent of annual ecosystem service production, including carbon storage, water production, climate regulation, and biodiversity resources, can vary from year to year with precipitation patterns (Borchert et al., 2002; Maass et al, 2005). The extent of natural inter-annual variability in TDF phenology in response to water availability and as a function of secondary succession is poorly understood and deserves the attention of tropical forest management and conservation efforts.

Studying the timing of leaf expression in TDFs provides important insights to the variability of forest productivity in response to changing micrometeorological conditions. As accelerating changes in global climate threaten to change precipitation patterns in many tropical semi-arid regions (Meir and Pennington, 2011), these changes will likely introduce undesirable stressors in the continental semi-arid tropics where ecosystems such as Tropical Dry Forests often exist in a fine balance between water scarcity and severe drought. Since TDF productivity is tightly linked to water resources, which in turn are highly variable across space and time, remote sensing methods for assessing TDF phenology must be both accurate and reliable in order to evaluate current baselines for tropical forest productivity and to detect climate change related alterations in forest phenology.

Remote Sensing of Vegetation with MODIS

Satellite remote sensing systems have become the tool of choice for landscape scale vegetation mapping, monitoring, and modelling in the 21st century due to the spatial extent and repeat capabilities of observation (Kerr and Ostrovsky, 2003, Xie et al., 2008). Specifically, spectral vegetation products from the MODerate resolution Imaging Spectroradiometer (MODIS) on board NASA’s Terra and Aqua Earth observation science satellite platforms, have been widely used for studying the temporal behaviour of land surface vegetation since the years 2000 and 2002, respectively. The MODIS land surface team offers several global repeat coverage spectral vegetation index (VI) products like the popularized Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI), the latter which improves issues with atmospheric correction, index saturation in dense forests, and soil background effects (Boegh et al., 2002; Huete et al., 2003; Xiao et al., 2004). These freely available data sets are offered at 250 m, 500 m, and 1km spatial resolution at 16-day or monthly intervals and are some of the most commonly used inputs for regional and global scale modelling of environmental dynamics (Tucker et al., 2005; Xhang et al., 2006).

While the MODIS vegetation greenness index products (MOD13) are quality controlled, currently at level 5 pixel quality assurance and level 3 ground validation, some issues still remain due to common challenges with moderate resolution remote sensing such as atmospheric correction, cloud contamination, land cover classification, spectral mixing within pixels, and sensor degradation (Myneni, et al., 1995; Malenovsky et al., 2009). In fact, proper land cover classification, an integral component of the MODIS look-up table algorithms for vegetation products, has been shown to remain a challenge in TDFs due to the extreme seasonality of this ecosystem (Sanchez-Azofeifa et al, 2003). Not only do TDFs suffer from frequent pixel cloud contamination during the rainy growing season, during the dry season when pixel quality is best they are often incorrectly classified as woody savannahs rather than broadleaf forest land cover due to the lower than predicted Leaf Area Index. Furthermore, TDFs tend to respond dramatically to precipitation events during the dry to wet season transition, and can flush out a full leaf canopy in less than two weeks making it easy to miss extreme changes in leaf area based on infrequent satellite observation. This combination of remote sensing challenges can cause phenology monitoring efforts from satellite to be inaccurate and misleading to users who are unaware of the data product limitations.

Here I investigate how the standard product MODIS vegetation greenness indices perform compared to near-surface canopy bi-hemispherical radiometric monitoring systems installed at several locations within regenerating plots of secondary Tropical Dry Forest in southeastern Brazil, in a region containing many of the last conserved fragments of the once widely distributed South American continental TDF biome. I ask the following questions in order to assess whether moderate resolution satellite remote sensing is sufficient for monitoring TDF phenology: a) How do direct comparisons of in-situ vegetation indices compare to MODIS satellite products across a gradient of TDF successional forest stages, b) how do multi-year time series trends of vegetation greenness indices compare between ground and satellite observation platforms, and c) are there significant differences in canopy phenology transition dates as detected using in-situ daily vs coarser temporal resolution satellite observations.

MATERIALS & METHODS

Study Site

The study plots are located within Mata Seca State Park, a 10,281 ha TDF (Holdridge life zone) conservation unit designated in 2000 and managed by the Minas Gerais' State Forestry Institute (IEF). The park is situated on flat, nutrient rich soils in the Sao Francisco river valley in the Municipality of Manga, Minas Gerais, Brazil between 14°48'36" – 14°56'59" S and 43°55'12" – 44°04'12" W. The climate of the region is tropical semi-arid (Köppen's classification), characterized by a severe seven month dry season which extends from April to October. Average annual precipitation is 900 mm with an average temperature of 24.8°C. This conservation area, comprised of a matrix of old growth and regenerating secondary forest stands with 1,500 ha of abandoned pasture and cropland, is a core research site for the Tropi-Dry Project supported by the Inter-American Institute for Global Change Research (Sanchez-Azofeifa et al., 2014). A chronosequence of long term ecological research plots at different stages of TDF succession were categorized into early stage (5-20years), intermediate stage (20-50 years) and late stage (>50 years) based on forest structure rather than absolute stand age following the methods of Kalacska et al. (2004; 2005) (see also Madeira et al. 2009).

Four plots along a 5 km transect were selected for this study, an early, an intermediate, and a late stage secondary forest site, as well as a recently abandoned pasture plot. The abandoned pasture is characterized by a 2-3m tall canopy of grasses and shrubs, and the early, intermediate, and late forest canopies have mean tree heights of 8 m, 15 m, and 22 m, respectively. Each forest stage has distinct differences in tree basal area and canopy vertical strata; for more details on forest stage characteristics see the methods by Madeira et al. (2009). Information on the sampling approach of the plot selection and spatial autocorrelation avoidance, to ensure statistical independence, can also be found in Madeira et al. (2009).

Canopy observation towers were installed in the early and intermediate stage plot in 2007 and in the late stage and pasture plots in 2010 and 2012, respectively, for continuous forest phenology monitoring using radiometric sensors. Hemispherical silicon pyranometers (Apogee SQ-110) and quantum sensors (Apogee SQ-110) were used at each tower to separately measure both downwelling (incident) and upwelling (reflected) shortwave solar radiation from 350-1100 nm and Photosynthetically Active Radiation (PAR) from 400-700 nm at 5m to 10m above the forest canopies. The 85 degree field of view from the radiometric sensors provide a viewing radius just over ten times the sensor's height above the target, resulting in a circular canopy footprint with a diameter between 100m and 150m (Figure 4-1). Undesirable tower reflectance effects were minimized by mounting the sensors at the end of a three meter boom off the towers.

Spectral Vegetation Indices

In-Situ Sensor Data

Synchronized above-canopy radiometric observations were sampled each 30 seconds, then averaged and logged at 15 minute intervals. Tower based NDVI was calculated following the methods of Wilson and Meyers (2007) in order to approximate red (ρRED) and near-infrared (ρNIR) reflectance. The tower EVI, properly called EVI2, follows the two-band method of Jiang et al (2008) and Rocha and Shaver (2009), using a standard gain (G) of 2.5 and a soil-adjustment (L) of 1. These EVI2 parameters were shown to be optimal in relating two band (red and NIR) indices to MODIS EVI which includes a third band in the blue spectrum (Jiang et al, 2008). To minimize high solar zenith effects the tower NDVI and EVI2, hereafter called tower EVI, values were derived using observations taken within 30 minutes of solar noon (11:30 to 12:30) and cloud filtered for direct beam "black sky" radiation only based on a minimum incident PAR value of 1000 uE. Then these midday values were further aggregated to a daily mean time series called midday Tower NDVI or EVI. All ground data was uploaded into a cyber-infrastructure database for data visualization and data quality control denominated Enviro-Net (see: Enviro-Net.org, Zonta-Pastorello et al. 2011).

MODIS Data

The MODIS sensor data products used were collection 5 MOD13Q1 and MYD13Q1 vegetation indices (VI) obtained using the Oak Ridge National Laboratory DAAC MODIS land process subset tool. MOD13Q1 (on-board Terra) and MYD13Q1 (on-board Aqua) are both 16-day L3 global 250m NDVI and EVI time series. Since the only standard 8-day MODIS NDVI/EVI product is offered at 500m spatial resolution, which was too large for our comparative purposes, the two 16-day indices were combined to produce an 8-day time series, referred to here as MODIS 8-day. This derived 8-day composite allowed for more frequent comparisons with daily tower-based observations. These vegetation indices are derived from atmospherically corrected bi-directional radiometric surface reflectance values in the blue (469 nm), red (645 nm) and near-infrared (858 nm) MODIS bands that have been further quality control masked for clouds and heavy aerosols. These products were selected over the daily raw MODIS surface reflectance data since the pre-processed standard MODIS VI products are more readily accessed and commonly used by the scientific community (Shao et al., 2011). The four 250m pixels used were co-located to the coordinates of the ground phenology observation towers and the pixel extent was confirmed using co-registered high resolution imagery to have a single pure land cover class, which was incorrectly classified as woody savannah in all cases. The MODIS time series data were further subset to match the temporal extent of the in-situ time series including seven growing seasons from 2007 to 2014.

Data Analysis

Least Squares Regression

Before linear regression analysis were conducted, time series data from both MODIS and tower observations were first de-spiked using a supervised median filter method that only removed erroneous data points that were not consistent within or between the ground and MODIS time series. These errors were due to sporadic sensor failures for the tower data and from errors in the

MODIS algorithm when cloud contamination was evident (typically values of 0, see Huete et al., 2002).

The MODIS 16-day maximum value composite product selects the reflectance values based on the best available data in the 16 day period. This means that the spectral vegetation index value provided may not match the exact date for ground comparisons. I calculated the 16 day average and maximum daily tower NDVI and EVI value in the MODIS composite period for both the Aqua and Terra products and found that these tower composites did not perform better in regression results than the individual tower VI values matching the 16 day interval date. Therefore, temporally matching 8-day interval tower midday VI data from each of the four study sites were regressed against the corresponding MODIS 8-day VI products. The resulting linear regression results along with the residual standard error of the models are reported in Table 4-1. In addition, the spline interpolated daily MODIS NDVI time series from both Aqua and Terra, used in the canopy phenometrics analysis, was regressed against the daily tower NDVI.

Canopy Phenometrics

Canopy seasonal growth phases, or phenophases, are grouped into four periods by deciduous leaf physiology, a) green-up, the period of photosynthetic biomass development including leaf bud burst and rapid leaf expansion b) canopy maturity, when leaf expansion has stabilized, peak greenness is maintained and canopy photosynthetic function is most active, c) leaf senescence, when photosynthetic pigments are degraded and leaf abscission begins, and d) canopy dormancy, when the majority of the plant canopy has become leafless and physiologically inactive for the dry season. Jonsson and Eklundh (2002) and Zhang et al. (2003) demonstrated that metrics based on the geometry and change points in a canopy greenness time series curve, or phenology curve, called phenometrics, could be used to quantify and compare inter-annual parameters of vegetation seasonality. The phenometrics examined for the late stage TDF include the onset and length of each phenophase, the length of the growing season and dry season specifically, and how they compare between tower-based and satellite time series.

For the seasonality, or phenometric, analysis, a curvature rate of change method was applied to the canopy greenness time series to detect seasonal transition points based on local maxima and minima of the time series derivatives, as opposed to the signal amplitude threshold commonly applied to remote sensing phenology studies (Jonsson and Eklundh, 2002). Curve derivative analysis allows for earlier detection of change points that denote the onset of each phenophase (Zhang et al., 2003). The de-spiked time series were gap filled and smoothed using a cubic spline interpolation method with a smoothing parameter of 1 (Igor Pro software) to obtain a daily MODIS time series - from the Terra, Aqua, and combined 8-day MODIS VIs - for temporal congruency with the tower observations. The smoothing parameter was found to sufficiently reduce short-range noise in the time series to minimize excessive change point detection for the derivative analysis, while limiting over-smoothing. Spline smoothing has an advantage over other time series smoothing, like simple moving averages, to avoid shifting temporal features and compromising the integrity of the original time series for accurately identifying the position of phenophase onset dates (Hermance et al, 2007).

The local maximum and minimum of the first derivative were used to locate the greatest rate of annual greenness increase and decrease during canopy green-up and brown-down. The difference between these dates is used as the first method (M1) for determining the length of the growing season (LGS) and length of the dry season (LDS). The local maximum and subsequent minimum of the second derivative during greenness increase are used to determine the onset of green-up and onset of canopy maturity, respectively, while the reverse signals, the local minimum and subsequent maximum, of the second derivative during VI decrease are used to select the dates of leaf senescence onset and the onset of canopy dormancy. The second method (M2) for determining the LGS is determined by the difference between the date of green-up onset and the date of the end of the senescence period to account for the entire period when leaves are present in the canopy.

The M1 approach using the first order derivative is less sensitive to short-term temporal variability in the time series which is amplified with each successive differentiation, thus the M2 approach to measuring seasonality based on the second derivative can be challenging to determine objectively, but is more physiologically representative of the full duration of canopy photosynthetic activity. These two methods for growing and dormant season length are compared and contrasted. All phenology transition dates are reported in day of year (DOY) from 001 on January 1 to DOY 365 on December 31 each year (see tables in appendix).

Proxy Productivity

The area under a greenness phenology curve has been used to represent primary productivity of an ecosystem and is referred to as the proxy productivity (Jonsson and Eklundh, 2002). The accumulated proxy productivity over three growing seasons, 2011-2014, was compared between the tower-based and combined 8-day MODIS greenness curves at the late stage TDF site. To compare the two curves with different amplitudes, and to account for absolute differences in the indices, the smoothed, gap-filled data was normalized to the maximum and minimum NDVI/EVI values in the time series which rescaled the range of the VI data from 0 to 1. This ensured that only observation differences between MODIS and tower VIs in the temporal domain were emphasized, rather than in the spectral domain. The integral of the normalized time series was then compared for differences in accumulated productivity estimates.

RESULTS

Greenness Trends and Forest Successional Stage

Observation of multi-year forest greenness trends showed notable differences in amplitude between forest successional stages with the late succession stage forest generally having a higher mean NDVI and EVI during the peak of the growing season and the bottom of the dry season (Figure 4-2). Minor differences in greenness amplitude were found between the three age classes of forest compared to the notable difference comparing the pasture greenness to the forest sites for both tower and MODIS observations. In addition, the early forest stage displayed more similarities in VI amplitude with the late stage forest than the intermediate stage stand. Worth noting is the lower than average EVI values produced during the first monitoring year of the late stage forest tower observations (2010/2011) which were due to improper placement of the reflected radiometric sensors and excess understory clearing of vegetation during site construction. Before correcting this sensor placement and vegetation disturbance error, the mean EVI was even lower than the intermediate stage forest, revealing the importance of minimizing vegetation disturbance during study site installation (Figure 4-2).

All sites showed similar temporal trends in overall seasonality with a few exceptions. The early stage forest appears to retain a higher tower-measured greenness during the senescence period than the other forest sites. There was also more noise present in the tower data for the early and intermediate sites immediately prior to green-up. Lastly, the abandoned pasture site had the most seasonal fluctuations in greenness during the growing season, likely due to greater water stress than the forested sites (Figure 4-2).

When daily tower and 8-day MODIS time series were plotted together (Figure 4-3) it became evident that the MODIS phenology curves had a greater seasonal amplitude than the tower trends, with this being more pronounced in the NDVI time series compared to the EVI. While the tower NDVI gradually decreased during leaf senescence, the MODIS NDVI very quickly decreased going into the dry season and fell to seasonal minimums between 10% and 30% lower than the tower NDVI. While the dormant state EVI values were also lower for the MODIS time series compared to the tower, they decreased at a more similar pace and typically remained within 5% to 15% of each other (Figure 4-3).

It was difficult to make further comparisons between the sites with the tower data due to equipment failures reducing the extent of temporal overlap between time series (Figure 4-2). The greatest amount of noise in the tower VI time series occurred near the end of the dry season when the forest canopy was devoid of any leaves. Large spikes in the NDVI and EVI can be seen in the weeks immediately prior to the onset of leaf flush in response to soil wetting from the first seasonal rainfall. In contrast to the tower data, all of the MODIS VI time series were found to have one or more zero values present which was unexpected for the QA/QC data product. Note that all the zero values for MODIS data were found during October to March during the rainy season, with nearly all of them being in November, the month with the greatest rainfall and cloud cover. In this regard, the daily time series tower data should be viewed as the reference canopy state for periods when the MODIS time series tends to show large sporadic increases or decreases in greenness. These sporadic changes are not likely representative of rapid biophysical changes in leaf area or chlorophyll content, rather, they are likely due to transient signal interference.

Tower vs. MODIS Linear Regression

Linear least squares regression between tower and MODIS VI paired 8-day time series revealed that NDVI trends, on average, agreed better than EVI trends when all observations were combined (NDVI: $R^2 = 0.78$, EVI: $R^2 = 0.83$; df = 595). At the individual plot level there were no differences found between NDVI and EVI correlation strengths for the pasture and intermediate forests, with 76% and 80% of the variability explained, respectively. These results also indicate that the NDVI had a 6% higher coefficient of determination (R^2) than the EVI at the early stage forest, and 15% higher in the late stage forest (Table 4-1). It is important to note that the strength of the correlation between the tower and MODIS VIs is an indicator of agreement between the temporal dynamics of the two time series and does not describe similarities for the absolute values of the vegetation indices, that relationship is described by the linear offset and residual error of each regression analysis.

Residual errors of each regression analysis were described and compared using the residual standard error (RSE) to indicate the accuracy of the linear models. The residual errors were, on average, lower for the EVI relationships at 0.074 RSE than for NDVI at 0.083. The RSE ranged from 0.09 for the NDVI comparison in the intermediate forest to as low as 0.061 for the EVI comparison in the abandoned pasture plot (Table 4-1). Figure 4-3 shows the data used in the regression analysis and Figure 4-4 shows the degree of scatter between the two temporally synchronized observations for each site. Further analysis on the residual errors for the regression analysis revealed that 75% of the total accumulated residual errors resulted from just 8-15% of the data points in any of the linear models and only occurred during October to December, and from April to May. Reviewing the comparative time series, it can be seen that these large agreement errors occur during periods of most rapid changes in canopy structure, either during leaf flush or senescence.

Ground vs. Satellite Seasonality Metrics

Only the late stage forest tower provided a sufficiently reliable long-term data set for comparing ground-truthed phenometrics with satellite data over multiple years, therefore, the late stage TDF was the only plot used in the seasonality comparison. The tower measurements revealed that the onset date of the green-up phenophase did differ between 2011, 2012, and 2013 by nearly three weeks, and that NDVI always increased before EVI, sometimes up to 13 days before (in 2013). Despite this temporal variability on leaf onset between the two indices, the length of the green-up remained remarkably constant at 20 to 21 days independent of year or index used.

In the late successional stage, the canopy reached maturity between day of the year (DOY) 305 and DOY 335 all three years, but again, these dates differed between indices and were found to be between four to twelve days earlier in the NDVI time series. The length of the mature canopy phenophase was fairly consistent between years, from 151 days in 2011-2012, to 160 days in 2012-2013. The canopy senescence period started around DOY 95 or 100 for both 2012 and 2014 based on the NDVI and EVI, respectively, but started nearly a full month later in 2013. Similarly, the onset of complete canopy dormancy occurred later in 2013. The largest disagreement between tower NDVI and EVI was for the dormancy onset transition date, ranging from 8 days in 2013 to 30 days in 2012. So despite the late start of the bud burst in 2012 by several weeks compared to 2011 and 2013, the length of the 2012-2013 growing season (LGS) from the onset of green-up to canopy dormancy (LGS-M2) was consistent within a few days of the 2011-2012 growing season length at 204 days, the exact same number of days as measured for the 2013-2014 season.

We observed very weak agreements between phenology transition dates derived from near-surface daily observations and those observed from MODIS satellite for both 16-day and 8-day time series composites (see tables in appendix). The satellite NDVI time series generally had larger discrepancies with the tower phenophase transition dates than the EVI series. On average, the Terra MODIS 16-day composite differed from the tower observations more than Aqua, both for individual transition dates and for the length of phenophases, but this pattern was inconsistent across phenophase periods. In many cases, the Aqua 16-Day composite was closer to the tower-based dates than the combined 8-day time series (Figure 4-5 and Figure 4-7).

For the two discussed methods of measuring the seasonal duration of canopy photosynthetic activity and dormancy, or length of growing season, the second derivative start and end of season method (M2) was found to have greater variability and more temporal disagreements with the tower observations of TDF seasonality as expected compared to the M1 approach, based on the 1st derivative. Tower-based measurements of growing season length (LGS) averaged 179 days based on M1 and 202 days based on M2 across the three observation years. A 20 day difference in the LGS, as found between season start and stop methods M1 and M2, roughly represents a 10% difference in photosynthetic period for a given year. Estimated growing season length varied between 6 and 69 day longer than tower derived LGS using the M2 for all satellite NDVI time series and between 10 days shorter to 35 days longer with the EVI. In contrast, the M1 estimates for the LGS ranged between 5 days shorter to 31 days longer than the in-situ measured season length with the NDVI, and between 19 days shorter and 28 days longer based on the satellite EVI. Such a large range in estimated number of days of canopy leaf expression results in up to 30% uncertainty in growing season length from satellite time series, depending on the temporal resolution used.

Ecosystem Productivity

After integrating the normalized tower and 8-day MODIS composite time series and comparing the accumulated greenness as a proxy for productivity very minor differences were found after three years between the in-situ and satellite measurements. Figure 4-8 shows how the cumulative productivity increases with each growing season and remains constant during canopy dormancy. The NDVI curves were very similar and after three seasons the MODIS NDVI total productivity was only 2% greater than the tower. The EVI curves had some notable differences, while the mid-season MODIS EVI dropped several times and the tower EVI did not, the cumulative greenness value of the MODIS curve was just 1% less than the tower due to earlier onset of green-up.

DISCUSSION

Direct comparisons of long term, multi-annual measurements of vegetation greenness from satellite and near surface remote sensing are rare in the tropics due to the challenges associated with implementing and maintaining sensitive radiometric instrumentation. This study from a TDF in southeastern Brazil revealed that there are several advantages to near-surface remote sensing over satellite monitoring of forest phenology. In addition to the greater temporal frequency of the in-situ broadband forest canopy greenness indices compared to satellite observation, tower-based platforms further benefit from a lack of atmospheric interference. Therefore, near-surface sensing of vegetation phenology in this fashion provides an ideal approach for the validation of satellite observations to detect long term changes in TDF productivity due to climate-based stress, as well as to characterize ecosystem level vegetation structural progression during ecological succession.

Directly Comparing Indices

While direct comparisons of ground and MODIS vegetation indices showed strong correlations, there are several relevant factors that can account for the 10-25% range of scatter in the regressions and the modest standard errors, ignoring the relatively small differences in target footprints and the confounding effects of atmospheric corrections (Franch et al., 2012). Huete et al. (2002) showed that MODIS VIs correlated well with airborne radiometric measurements for areas with low to moderate vegetation densities, but correlations were very poor for forests. The sensor-target viewing geometry and reflectance functions become complicated for rough, non-lambertian target surfaces like those of tall, heterogeneous forest canopies (Li and Strahler, 1992; Gerard and North, 1997). In the temporal domain, Breunig et al. (2015) reported on the seasonal effects of solar illumination geometry variations in the MODIS NDVI and EVI of a Brazilian deciduous subtropical forest, and found that canopy reflectance anisotropies were significantly affected by changes in leaf area. The authors also found that the effect was more pronounced in the EVI. These factors likely contribute to the cross-comparison variations in our study.

Target proximity and directionality effects are also important with respect to light scattering and reflectance distribution above an old growth tropical forest where complex canopy structure and gap shadows can create significant anisotropies in reflected radiation (Ranson et al, 1994, Leblanc et al., 1997). These effects may introduce greater short-term reflectance signal bias at the near target viewing angles of tower-based sensors compared to satellite observations. To minimize this effect, it is recommended to place downward facing sensors sufficiently high above the forest canopy, at least 10 m, but this is often restricted by the logistics of building non-invasive structures within a protected, old-growth tropical forest upwards of 20-30m in height.

The variation in the strength and the regression slopes of the relationships found between in-situ and MODIS VIs differed between successional stages of this Brazilian TDF. Since the agreement between the two was slightly greater for the late stage forest than for the early stage and abandoned pasture, it could be that the lower canopy closure and total leaf area of the younger forest stage created higher variability between the vegetation indices (Sanchez-Azofeifa et al. 2009). Related to this is the relative contribution of understory vegetation in the reflectance signals. Close proximity of the tower sensors to the forest likely result in a greater contribution of the understory vegetation to the total reflectance at the tower than from the MODIS perspective, especially for early successional stages. For this reason, and due to the higher temporal resolution of the tower NDVI/EVI time series, any mistiming between overstory and understory leaf phenology would be more pronounced in the in-situ time series than from the 8 or 16 day MODIS observations. Ryu et al. (2014) recently showed that multi-layered forest canopies can exhibit significantly different timing between understory and overstory green-up events, and that the understory canopy development in a temperate deciduous forest was responsible for the MODIS based onset date of greenup rather than that of the overstory which was offset by about 10 days. This could also be a dominant mechanism for this TDF site given the presence of multi-layer canopies. The temporal decoupling of understory and overstory canopy development using MODIS time series has been demonstrated in boreal forests where the tree canopy is sparse (Pisek et al., 2015). Unfortunately, dense broadleaf canopies, like in mature TDFs, occlude such observations from optical satellite sensors, and as such more work needs to be done in-situ to understand the nature of multi-layered canopy phenology in TDFs. The effect of multi-layer phenology, as demonstrated by Ryu et al. (2014) can be more dominant in early and intermediate successional stages of a TDF, where dominant understory grasses and shrubs (with shallow root systems) can flush their leaves quickly after the first rains even before trees and lianas have a chance to respond (Kalascka et al., 2005; Maderia et al., 2009).

Another important distinction between the two observation systems that undoubtedly causes discrepancies in direct comparisons are the spectral bands used to produce the indices. Differences in spectral response functions of sensors is a major limitation in current cross-platform validation of earth observation sciences (Huang et al., 2013). While the MODIS standard VI products are narrowband centered on the red, near infrared, and blue (for EVI) wavebands, the tower-based products are broadband vegetation indices that approximate the red and NIR reflectance in the full visible and shortwave radiation spectrums. Theoretically, a narrowband NDVI or EVI should be more sensitive to changes in leaf area and chlorophyll content than a broadband version given the nature of the relationship between the absorption and reflectance features of green vegetation. This might explain why the tower based greenness seasonality appears more depressed than the MODIS time series at all four sites, seen in Figure 4-3. So while the MODIS time series contains more noise from sporadic data values, the enhanced greenness sensitivity of narrowband VIs might prove more useful than broadband radiometric VIs for leaf area index estimations in dense TDF stands where the relationship between spectral indices and biophysical parameters are known to saturate (Huete et al., 2002).

Lastly, the correlations found between MODIS and tower-based NDVI may be stronger than EVI since the MODIS 16-day maximum value composite method relies on reflectance values for optimal NDVI and the EVI calculations are based on the same values (Gao et al., 2003). So while a greater temporal agreement between tower and MODIS NDVI is observed here, this may be in part due to the temporal compositing of the standard 16-day products. Furthermore, the blue band reflectance used for 250m resolution EVI is obtained from the 500m pixel as this band is not available at higher spatial resolutions (Shao et al., 2011). In addition, the MODIS composite method makes exact matching between observation dates difficult as the actual date of reflectance value acquisition is not known. While a more accurate MODIS data set is available for scientific user group that includes the actual collection DOY for a given composite NDVI/EVI data point, rather than the 8-day interval date provided, the intent was to compare the ground data to the most commonly used MODIS standard VI products (MOD13Q1/MYD13Q1). That being said, the main objective of this paper was not to assess the absolute scale agreement in the NDVI and EVI dimensions between MODIS and tower platforms, and while this is worth exploring, the main contribution here relates to the temporal domain for assessing discrepancies in phenology observations.

Monitoring TDF Seasonality

Despite a long history of vegetation phenology research, there is still little agreement or standardization of phenometric definitions or methods for determining key transition dates in remotely sensed vegetation seasonality (Ahl et al., 2006; White and Nemani, 2003). This lack of agreement is contributing to discrepancies regarding the impact of global environmental and climate change on phenology driven ecosystems, which in turn can have significant impacts on many other schemes that may eventually need this information to estimate key variables (e.g. econometric models of ecosystem services). Curve amplitude threshold methods, applied to raw and normalized VIs, are often the simplest to implement and interpret but threshold values can be arbitrarily chosen and may not apply to all ecosystems equally. In addition, a threshold method only indicates start and end of season dates and cannot be used to determine the onset timing of each canopy development phases. Onset dates are required to assess the duration and rates of canopy green-up, maturity, and senescence which are important parameters to monitor closely in order to quantify TDF sensitivity to climatic change and variability, as well as to characterize ecosystem services associated to carbon, water and biodiversity. For these reasons the first and second order time series derivative methods were applied in order to identify phenophase transitions based on rates of curvature change in the smoothed vegetation indices rather than amplitude threshold approaches. The third derivative function can be used to locate earlier transition points closer to the onset of a change in curvature, but this method was not applied as it tends to be a far more subjective to analyst interpretation due to the strong sensitivity to signal noise in the original data. This approach also allows for the identification of peak rates of greenness increase and decrease based on inflection points, which is often what the 50% amplitude threshold values attempts to estimate to represent the start and end of season dates (Ahl, et al., 2006; Zhang et al., 2003).

It is worth noting that the transition dates selected for this study do not perfectly coincide with the onset of greenness increase or decrease. Rather these dates coincide with the peak rates of change that occur immediately (one or two days) following an increase in greenness or prior to a greenness decrease. In this way the method used avoids selecting artificial increases in the VIs that do not represent a significant biophysical change in the forest leaf area. Also worth discussing is the presence of increased low amplitude noise in both the tower NDVI and EVI in the weeks immediately prior to the green-up event. This is most likely due to the first rainfall events of the season wetting the soil and tree branches. These events cause rapid changes in surface water content, which in turn affects the visible and shortwave radiation albedos. It is important to stress that these short-term increases in the late dry season signal did not likely represent changes in photosynthetic biomass. When this effect was not filtered properly it was found to increase the

SOS date by over 2 weeks which is significant in TDF environments given the fast rate of leaf development that occurs right after the first rains arrive.

In this analysis there are large discrepancies between the canopy transition dates as observed from MODIS compared to the near-surface remote sensing tower observations. Much of this disagreement can presumably be attributed to the lower temporal resolution of the satellite product, and the MODIS data compositing methods. Greater intervals between observations in a time series leads to increased inaccuracies during interpolation, thus during periods of rapid canopy development at the onset of the rainy season and leaf wilting during drought, the MODIS 16-day products will fail to capture accurate transition dates for this TDF environment. Similarly, the maximum value composite approach, while beneficial for minimizing erroneous NDVI/EVI data, introduces greater uncertainty in determining accurate canopy phenology information by potentially missing important leaf area dynamics or leaf chlorophyll content transition events at the start and end of the growing season at the Mata Seca State Park.

As previously mentioned, the length of growing and dormant seasons are important phenometric variables for monitoring climate change in TDFs due to the responsivity of TDFs to water availability. Linkages between tropical forest phenology and climate variability are poorly understood compared to temperate regions where models of vegetation phenology, often based on growing degree-days, have become increasingly robust (Zhang et al 2004). More research needs to be done to relate TDF canopy biophysics with meteorological drivers. For example, multiyear variability in phenophase duration and transition rates may be an indicator of canopy stress or adaptive responsivity to uncharacteristic weather patterns. A slow start of season leaf development rate, represented by a longer green-up phase, may relate the effects of water limitations or reduced plant energy stores from a longer dry season or shorter growing season the previous year. A longer senescence period could be the forest’s response to rainfall late in the growing season, which can be a significant sink of carbon in years with longer growing seasons. Rainfall events early in the dry season when leaves are still present in the canopy can be more readily utilized than water made available late in the dry season when a second leaf flush may be required (Reich and Borchert, 1984). Such climatic events can impact tree mortality and species dynamics during forest succession and may be monitored over long periods using higher frequency satellite observations paired with detailed phenometric analysis.

TDFs do not present the typical challenges associated with most forest phenology assessment methods, as these are primarily targeted to temperate regions where snowfall typically interferes with the reflectance signals (White et al., 2014). In higher latitude forests, freezing temperatures and snow occur suddenly and canopy senescence is more often a rapid process. The greatest uncertainty in phenology transition determination in a TDF canopy was observed during the onset of senescence. The water stress tolerance of TDF vegetation and late season water pulses leads to a slow senescence of deciduous vegetation and instability in the greenness curve which does not provide a distinct enough change point for determining a single onset point for canopy senescence, specifically using an EVI time series. These results suggest using NDVI for selecting the onset of senescence in TDFs rather than EVI, and choosing the point of most rapid decline in canopy greenness based on the first order derivative when determining the end of season for high temporal resolution VI observations.

CONCLUSIONS

This study on the linkage between near surface remote sensing observations and MODIS NDVI and EVI products produced a series of observations relevant to the climate change and ecosystem services scientific and decision making community. Specifically (i) Tropical Dry Forests serve as important biological indicators of shifting climate patterns and land-atmosphere moisture dynamics in the semi-arid tropics, but are highly fragmented and degraded with little known about their patterns of growth and recovery during secondary succession, therefore a higher level of attention is needed in order to fully understand the response of tropical ecosystems to global environmental change, (ii) standard MODIS vegetation index time series products MOD13Q1/MYD13Q1 do represent the phenology of this Brazilian ecosystem well enough for qualitative purposes, but for more accurate quantitative assessment and inter-annual comparisons of seasonal productivity a temporal resolution time series greater than 8 days is required. MODIS standard products with maximum value composite time series should not be used to determine phenology transition dates where temporal accuracy greater than the composite window of 16 days is required and (iii) the MODIS collection 5 NDVI/EVI product still suffers from frequent cloud contamination during the onset of the rainy season when the rate of leaf growth is greatest and changes in biosphere-atmosphere exchanges are most significant, limiting the application of these freely available data to forthcoming needs emerging by governments interested on linking MODIS derived products to decision making tools.

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TABLE LEGENDS

TABLE 4-1. Results of linear regression between tower and MODIS observations of NDVI and EVI (in the general form: MODIS.VI=slope*Tower.VI + offset). Numbers in bold indicate the highest coefficient of determination (adjusted R^2) and the lowest residual standard error (RSE).

TABLE 4-2. Canopy phenology phase onset day of year (DOY) for the late successional stage TDF as estimated from tower and MODIS greenness observations.

TABLE 4-3. Duration in number of days of TDF canopy phenophases and length of growing season (LGS) for late successional stage forest based on tower sensor observations (in-situ). Differences in phase length between MODIS and tower time series are reported below in-situ durations. LGS method 1 (M1) is based on the peak greenness increase/decrease dates and LGS method 2 (M2) is based on the onset of green-up and dormancy dates.

FIGURE LEGENDS

FIGURE 4-1. Location of the Mata Seca State Park, Minas Gerais, Brazil. The figure shows the four locations of the 250m MODIS pixels selected for vegetation greenness time series comparisons with radiometric tower observations. The location of the near-surface remote sensing tower footprints within the pixel is also presented. Study plots include an (a) abandoned pasture site (b) and an early (c), intermediate (d), and late stage secondary tropical dry forest.

FIGURE 4-2. Time series for all unfiltered MODIS and tower NDVI and EVI observations from 2007 to 2014 comparing greenness trends in an abandoned pasture (grey) and an early (yellow), intermediate (orange), and late (blue) stage secondary tropical dry forest. MODIS data are 8-day composites from combined Terra and Aqua 16-day products. Tower observations are daily midday means filtered for clouds. Growing season begins in October-November and ends in April-June.

FIGURE 4-3. Direct time series comparisons of MODIS 8-day composite (black) NDVI and EVI paired with daily observations from near-surface phenology towers (grey) at all four study plots in a tropical dry forest conservation park in southeastern Brazil.

FIGURE 4-4. Linear regression plots showing the scatter between tower and satellite measurements of NDVI and EVI(2) for three different successional stages of tropical dry forest and their precursor land use/cover class, abandoned pasture land. Please refer to Table 1 for a summary of the linear regression statistics.

FIGURE 4-5. Time series scatterplot comparison of spline interpolated daily MODIS NDVI (based on 16-day Aqua and Terra composites and combined 8-day product) directly compared to tower daily NDVI. Interpolated Terra tends to overestimate NDVI, and interpolated Aqua tends to underestimate NDVI compared to the ground daily tower time series observations. The combined 8-day product has the highest correlation (R^2=0.98) but also the highest slope of regression. The interpolated Terra product, with the lowest slope and offset, shows the closest 1:1 relationship with the tower data.

FIGURE 4-6. A single year comparing phenophase transition dates as estimated from daily tower NDVI observations (black) and MODIS satellite 8 (blue) and 16 day time series (grey and yellow). Greater variability in transition dates is seen during leaf senescence rather than green-up most likely due to greater spatial asynchrony in tropical dry forest brown-down.

FIGURE 4-7. Difference in duration of late stage secondary tropical dry forest phenophases between in-situ measurements and three MODIS time series for three growing seasons and two dormant periods between 2011 and 2014. All units are in days.

FIGURE 4-8. Differences in a three year trend in accumulated proxy-productivity of late stage tropical dry forest based on in-situ and satellite vegetation greenness indices. The minimum and maximum NDVI and EVI values were rescaled from 0 to 1 in order to normalize the curves and allow direct comparisons of the accumulated area under the curves representing forest productivity.

(TABLE 4-1)

	NDVI	*EVI*	*NDVI*	*EVI*	*NDVI*	*EVI*		*Significance*
TDF SITE	**Slope**	**Slope**	**Adj. R^2**	**Adj. R^2**	**RSE**	**RSE**	**df**	$p < 0.001$
Pasture	1.52	1.25	0.76	0.77	0.086	**0.061**	112	Y
Young	1.72	1.18	0.85	0.79	0.079	0.079	144	Y
Intermediate	1.66	1.38	0.81	**0.80**	0.09	0.071	179	Y
Late	1.63	1.27	**0.89**	0.74	**0.078**	0.086	161	Y

(TABLE 4-2)

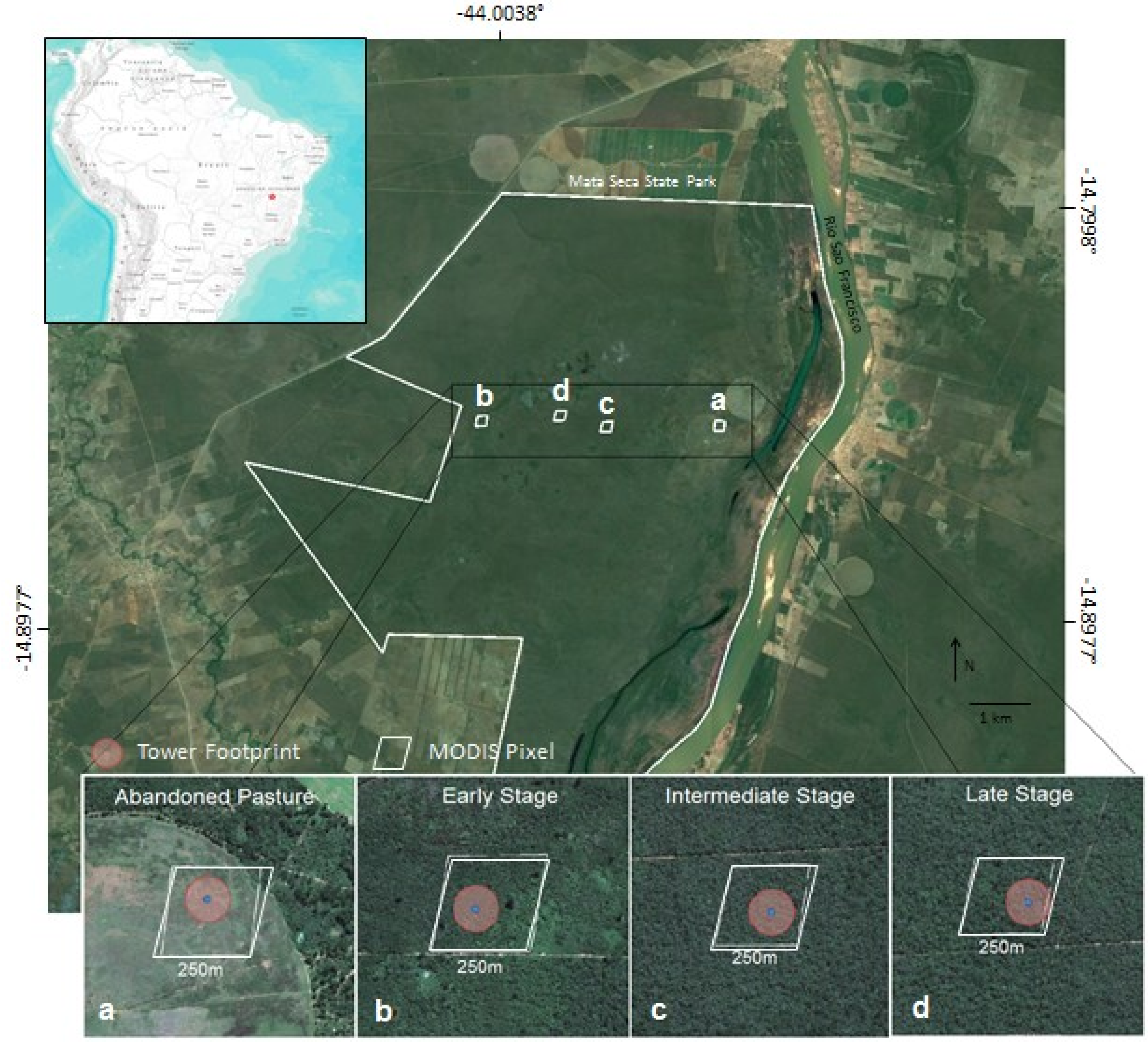
	NDVI	*EVI*	*NDVI*	*EVI*	*NDVI*	*EVI*
Onset of GreenUp	**2011**	**2011**	**2012**	**2012**	**2013**	**2013**
Tower Daily	289	292	305	314	283	296
MOD 8-Day	273	280	297	299	281	281
Terra 16-Day	260	261	281	282	271	286
Aqua 16-Day	277	278	300	314	302	288
	NDVI	EVI	NDVI	EVI	NDVI	EVI
Peak Green Increase	**2011**	**2011**	**2012**	**2012**	**2013**	**2013**
Tower Daily	297	302	314	324	294	308
MOD 8-Day	286	286	316	316	302	298
Terra 16-Day	273	270	298	297	295	292
Aqua 16-Day	287	297	320	322	311	312
	NDVI	EVI	NDVI	EVI	NDVI	EVI
Onset of Maturity	**2011**	**2011**	**2012**	**2012**	**2013**	**2013**
Tower Daily	309	313	325	335	305	317
MOD 8-Day	304	313	329	322	313	305
Terra 16-Day	294	278	316	315	319	303
Aqua 16-Day	295	310	331	332	320	320
	NDVI	EVI	NDVI	EVI	NDVI	EVI
Onset of Senescence	**2012**	**2012**	**2013**	**2013**	**2014**	**2014**
Tower Daily	95	99	120	130	93	98
MOD 8-Day	82	105	121	104	81	82
Terra 16-Day	73	72	124	93	97	81
Aqua 16-Day	120	104	124	109	89	96
	NDVI	EVI	NDVI	EVI	NDVI	EVI
Peak Green Decrease	**2012**	**2012**	**2013**	**2013**	**2014**	**2014**
Tower Daily	108	111	133	141	110	121
MOD 8-Day	128	115	133	128	130	94
Terra 16-Day	107	107	137	129	127	93
Aqua 16-Day	129	115	134	132	140	106
	NDVI	EVI	NDVI	EVI	NDVI	EVI
Onset of Dormancy	**2012**	**2012**	**2013**	**2013**	**2014**	**2014**
Tower Daily	118	148	144	152	122	134
MOD 8-Day	138	137	185	138	145	144

Terra 16-Day	137	136	189	142	146	145
Aqua 16-Day	137	169	174	142	147	147

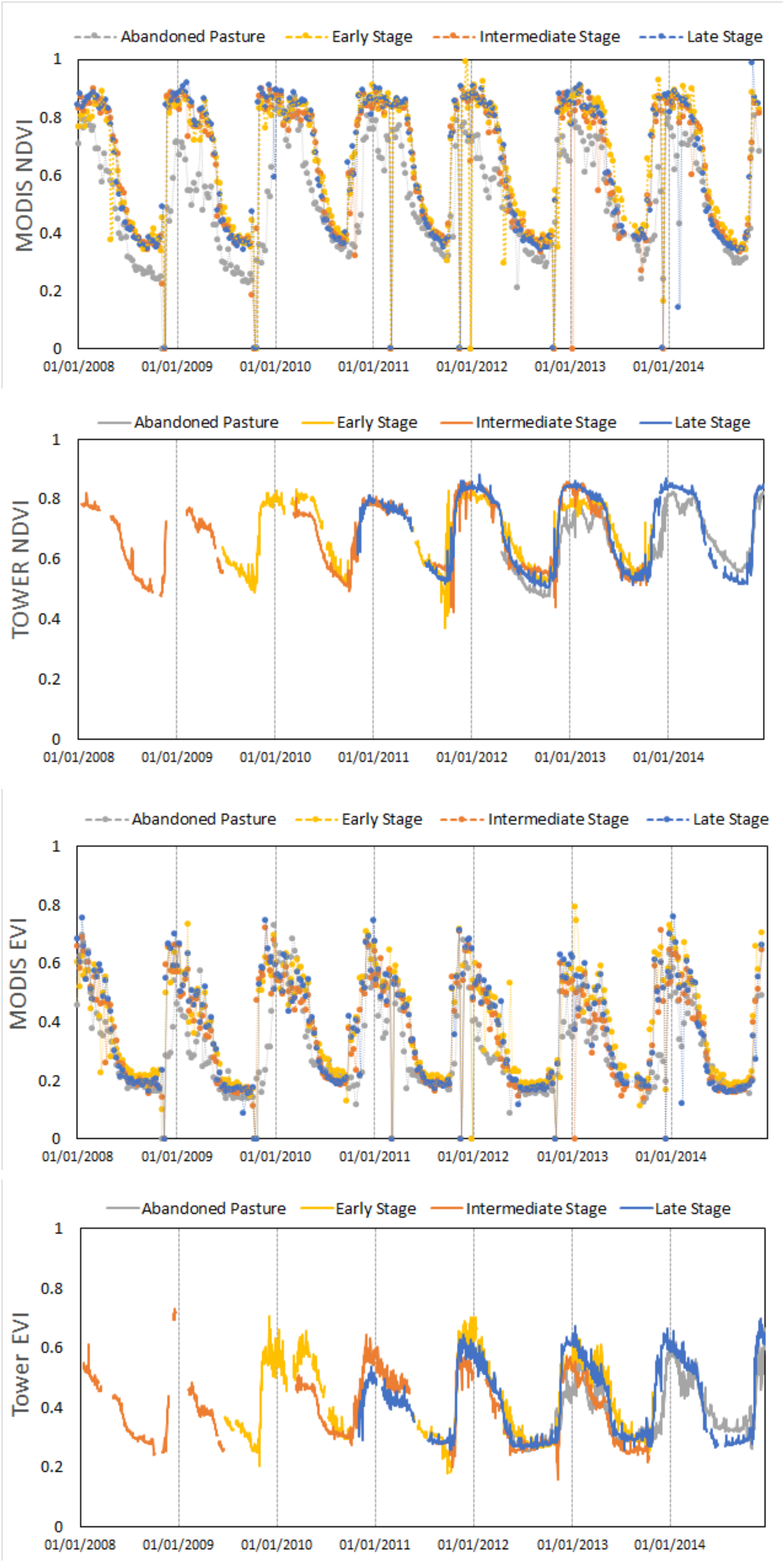
** = uncertainty in date due to multiple local max/min in derivative*

(TABLE 4-3)	*NDVI*	*NDVI*	*NDVI*	*EVI*	*EVI*	*EVI*
Green-Up	**2011**	**2012**	**2013**	**2011**	**2012**	**2013**
In-Situ Duration	20	20	22	21	21	21
MODIS 8-Day	+11	+12	+10	+12	+2	+3
Terra 16-Day	+14	+15	+26	-4	+12	-4
Aqua 16-Day	-2	+11	-4	+11	-3	+11
	NDVI	NDVI	NDVI	EVI	EVI	EVI
Maturity	**2011-12**	**2012-13**	**2013-14**	**2011-12**	**2012-13**	**2013-14**
In-Situ Duration	151	160	153	151	160	146
MODIS 8-Day	-8	-3	-20	+6	-13	-4
Terra 16-Day	-7	+13	-10	+8	-17	-3
Aqua 16-Day	+39	-2	-19	+8	-18	-5
	NDVI	NDVI	NDVI	EVI	EVI	EVI
Senescence	**2012**	**2013**	**2014**	**2012**	**2013**	**2014**
In-Situ Duration	23	24	29	49	22	36
MODIS 8-Day	+33	+40	+35	-17	+12	+26
Terra 16-Day	+41	+41	+20	+15	+27	+28
Aqua 16-Day	-6	+26	+29	+16	+11	+15
Dormancy	**2012**	**2013**		**2012**	**2013**	
In-Situ Duration	187	139		166	144	
MODIS 8-Day	-28	-43		-4	-1	
Terra 16-Day	-43	-57		-20	0	
Aqua 16-Day	-24	-11		-21	+2	
	NDVI	NDVI	NDVI	EVI	EVI	EVI
LGS M1	**2011-12**	**2012-13**	**2013-14**	**2011-12**	**2012-13**	**2013-14**
In-Situ Duration	176	184	181	174	182	178
MODIS 8-Day	+31	-2	+12	+20	-5	-17
Terra 16-Day	+23	+20	+16	+28	+15	-12
Aqua 16-Day	+31	-5	+13	+9	-7	-19
	NDVI	NDVI	NDVI	EVI	EVI	EVI
LGS M2	**2011-12**	**2012-13**	**2013-14**	**2011-12**	**2012-13**	**2013-14**
In-Situ Duration	194	204	204	221	203	203
MODIS 8-Day	+36	+49	+25	+1	+1	+25
Terra 16-Day	+48	+69	+36	+19	+22	+21
Aqua 16-Day	+31	+35	+6	+35	-10	+21

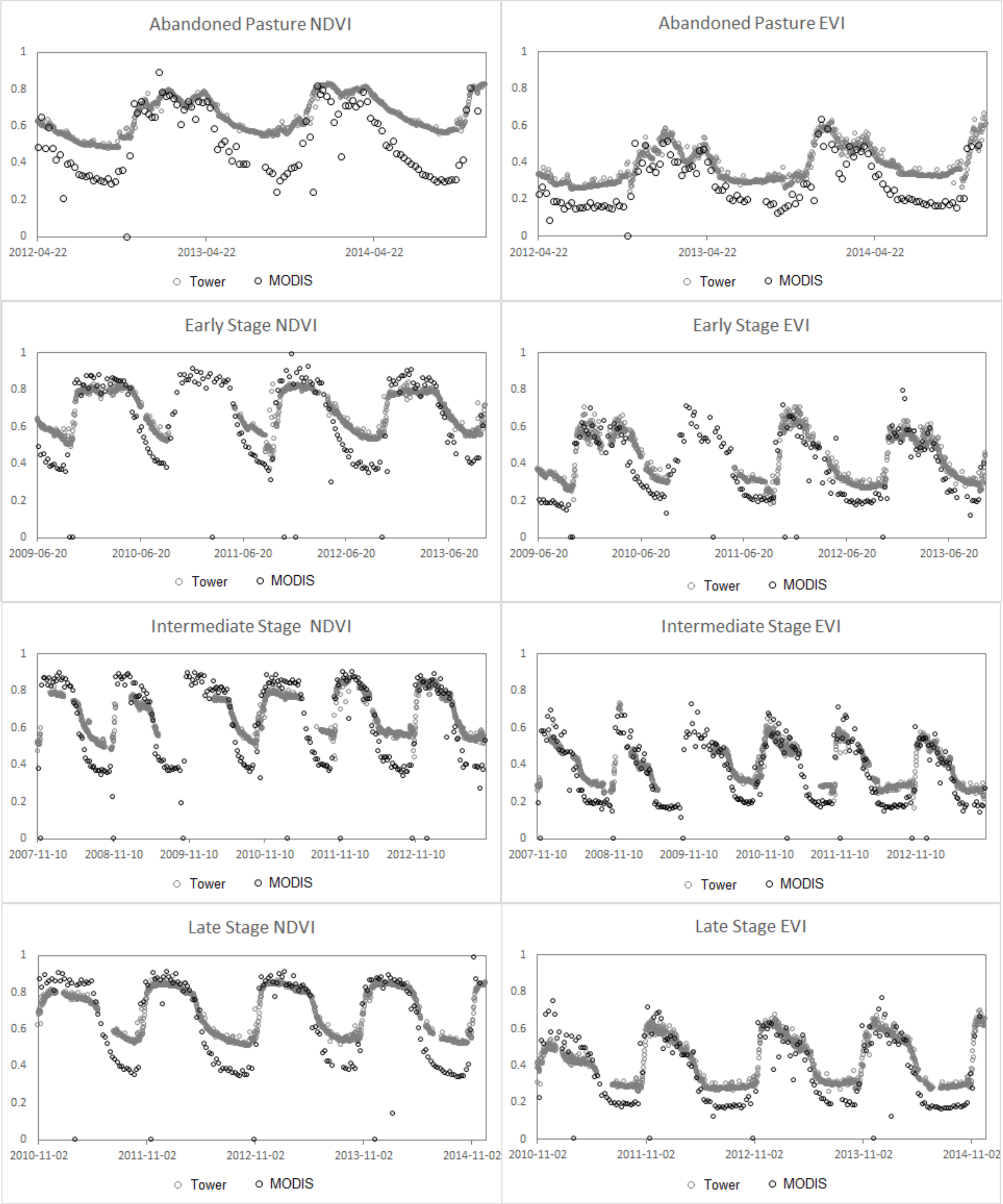
(FIGURE 4-1)


-44.0038°
-14.7998°
-14.8977°
-14.8977°
Mata Seca State Park
Rio Sao Francisco
b
d
c
a
N
1 km
Tower Footprint
MODIS Pixel
Abandoned Pasture
Early Stage
Intermediate Stage
Late Stage
250m
250m
250m
250m
a
b
c
d

(FIGURE 4-2)

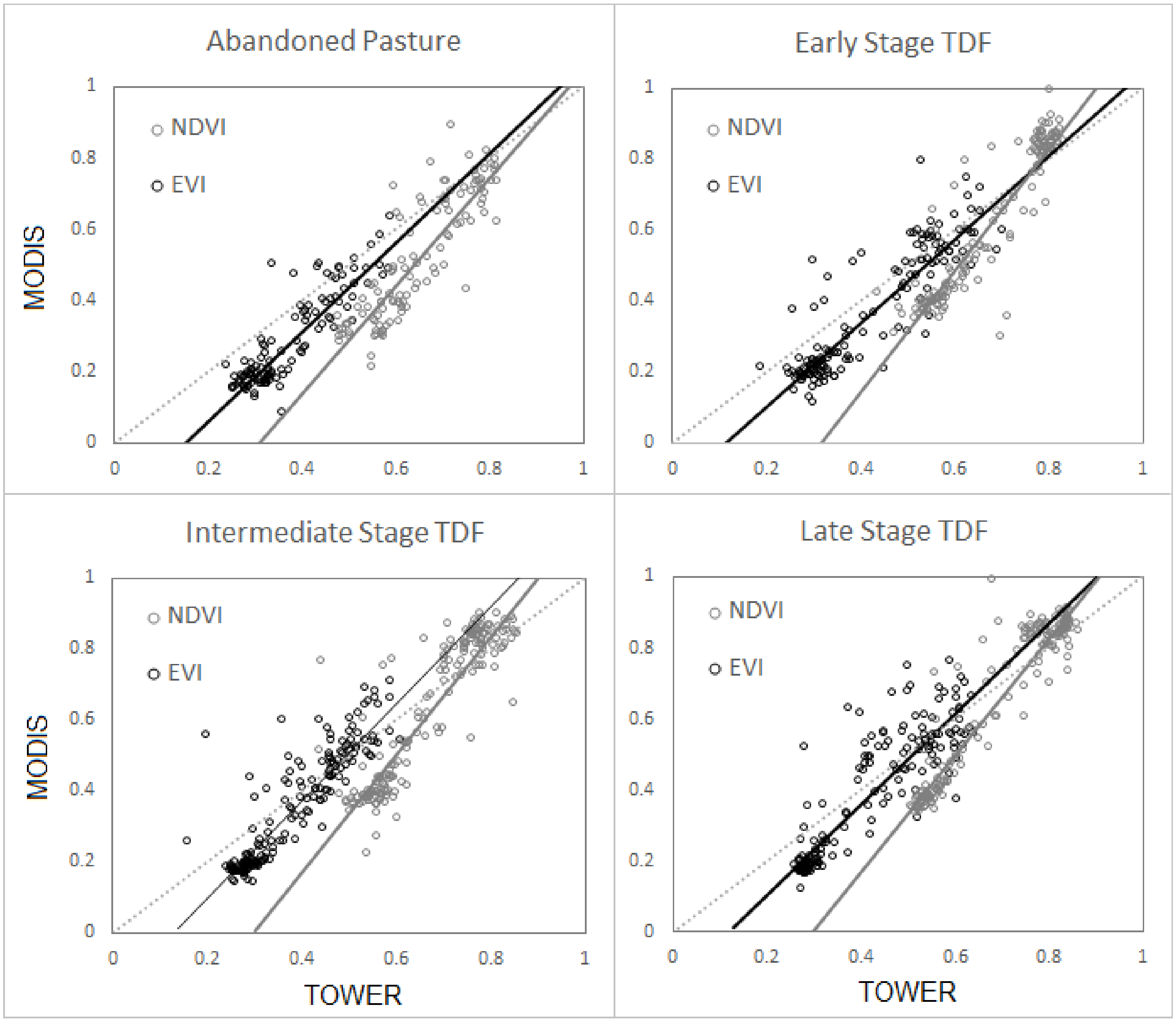

Abandoned Pasture
Early Stage
Intermediate Stage
Late Stage
MODIS NDVI
1
0.8
0.6
0.4
0.2
0
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013
01/01/2014
Abandoned Pasture
Early Stage
Intermediate Stage
Late Stage
TOWER NDVI
1
0.8
0.6
0.4
0.2
0
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013
01/01/2014
Abandoned Pasture
Early Stage
Intermediate Stage
Late Stage
MODIS EVI
1
0.8
0.6
0.4
0.2
0
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013
01/01/2014
Abandoned Pasture
Early Stage
Intermediate Stage
Late Stage
Tower EVI
1
0.8
0.6
0.4
0.2
0
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013
01/01/2014

(FIGURE 4-3)

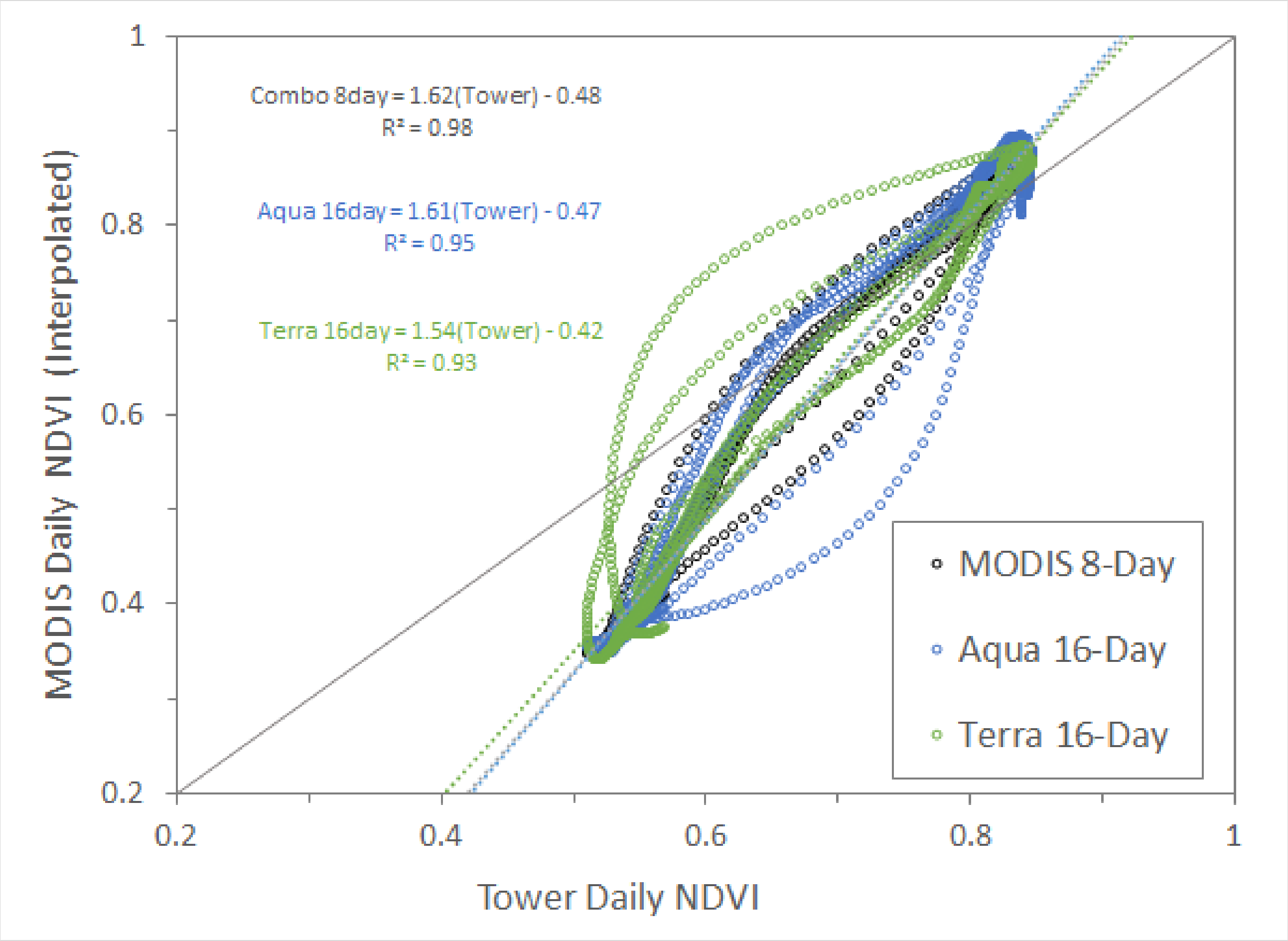


Abandoned Pasture NDVI
1
0.8
0.6
0.4
0.2
0
2012-04-22
2013-04-22
2014-04-22
○ Tower
○ MODIS
Abandoned Pasture EVI
1
0.8
0.6
0.4
0.2
0
2012-04-22
2013-04-22
2014-04-22
○ Tower
○ MODIS
Early Stage NDVI
1
0.8
0.6
0.4
0.2
0
2009-06-20
2010-06-20
2011-06-20
2012-06-20
2013-06-20
○ Tower
○ MODIS
Early Stage EVI
1
0.8
0.6
0.4
0.2
0
2009-06-20
2010-06-20
2011-06-20
2012-06-20
2013-06-20
○ Tower
○ MODIS
Intermediate Stage NDVI
1
0.8
0.6
0.4
0.2
0
2007-11-10
2008-11-10
2009-11-10
2010-11-10
2011-11-10
2012-11-10
○ Tower
○ MODIS
Intermediate Stage EVI
1
0.8
0.6
0.4
0.2
0
2007-11-10
2008-11-10
2009-11-10
2010-11-10
2011-11-10
2012-11-10
○ Tower
○ MODIS
Late Stage NDVI
1
0.8
0.6
0.4
0.2
0
2010-11-02
2011-11-02
2012-11-02
2013-11-02
2014-11-02
○ Tower
○ MODIS
Late Stage EVI
1
0.8
0.6
0.4
0.2
0
2010-11-02
2011-11-02
2012-11-02
2013-11-02
2014-11-02
○ Tower
○ MODIS

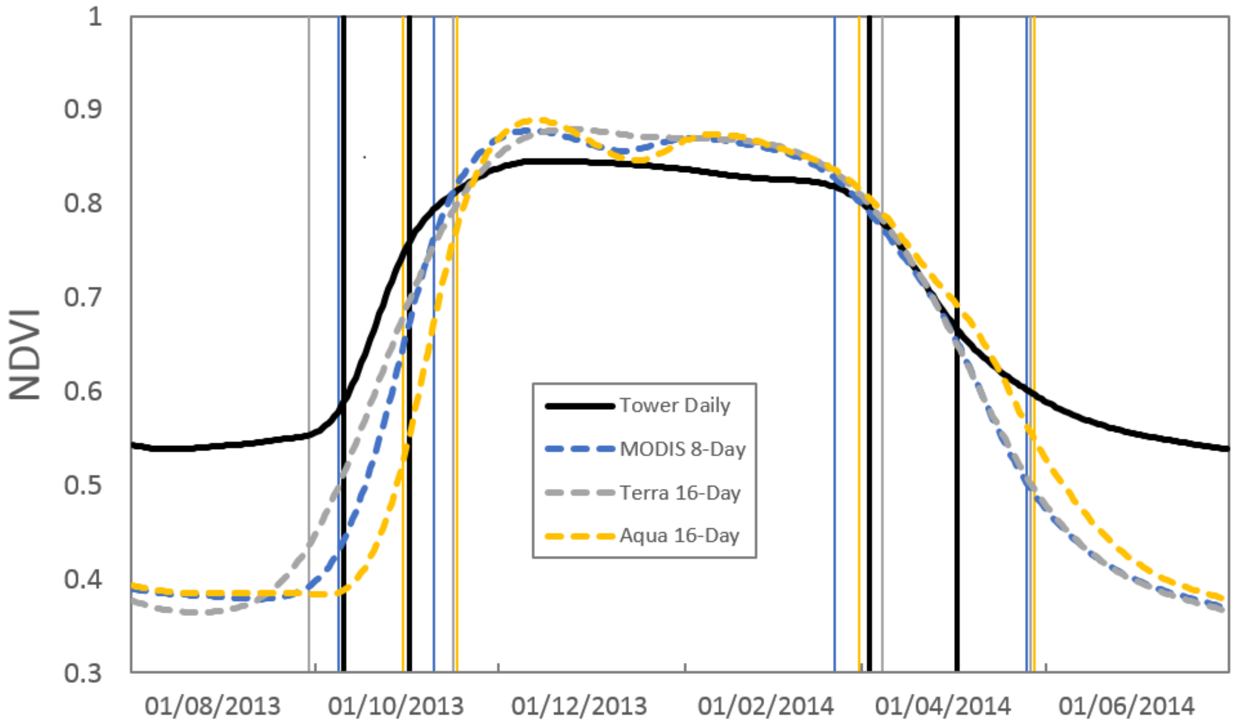
(FIGURE 4-4)


Abandoned Pasture
Early Stage TDF
Intermediate Stage TDF
Late Stage TDF
NDVI
EVI
MODIS
TOWER
0
0.2
0.4
0.6
0.8
1

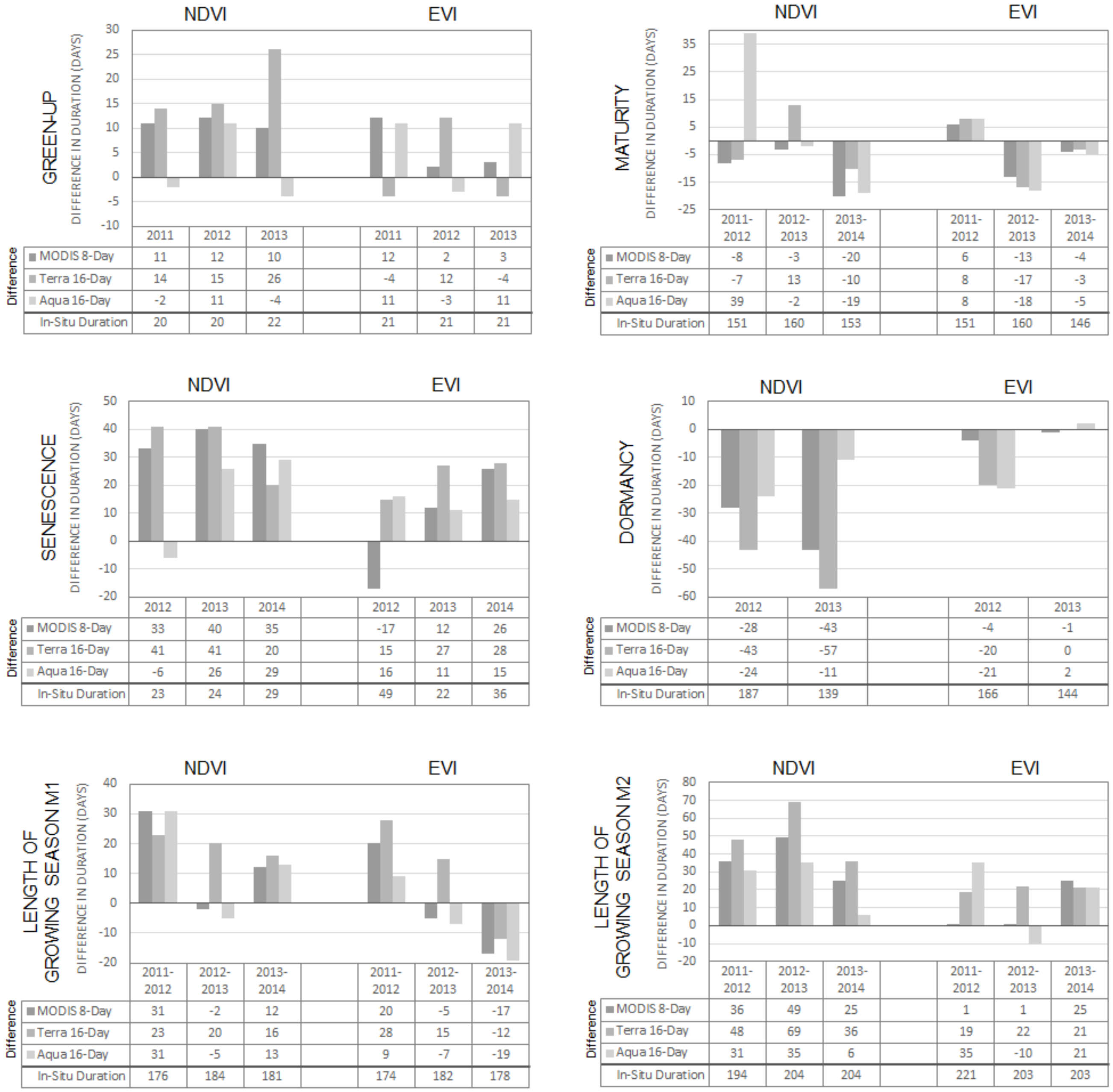
(FIGURE 4-5)


Combo 8day = 1.62(Tower) - 0.48
R² = 0.98
Aqua 16day = 1.61(Tower) - 0.47
R² = 0.95
Terra 16day = 1.54(Tower) - 0.42
R² = 0.93
MODIS 8-Day
Aqua 16-Day
Terra 16-Day
MODIS Daily NDVI (Interpolated)
Tower Daily NDVI
0.2
0.4
0.6
0.8
1

(FIGURE 4-6)


NDVI
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
01/08/2013
01/10/2013
01/12/2013
01/02/2014
01/04/2014
01/06/2014
Tower Daily
MODIS 8-Day
Terra 16-Day
Aqua 16-Day

(FIGURE 4-7)



GREEN-UP

	2011	2012	2013		2011	2012	2013
MODIS 8-Day	11	12	10		12	2	3
Terra 16-Day	14	15	26		-4	12	-4
Aqua 16-Day	-2	11	-4		11	-3	11
In-Situ Duration	20	20	22		21	21	21

MATURITY

	2011-2012	2012-2013	2013-2014		2011-2012	2012-2013	2013-2014
MODIS 8-Day	-8	-3	-20		6	-13	-4
Terra 16-Day	-7	13	-10		8	-17	-3
Aqua 16-Day	39	-2	-19		8	-18	-5
In-Situ Duration	151	160	153		151	160	146

SENESCENCE

	2012	2013	2014		2012	2013	2014
MODIS 8-Day	33	40	35		-17	12	26
Terra 16-Day	41	41	20		15	27	28
Aqua 16-Day	-6	26	29		16	11	15
In-Situ Duration	23	24	29		49	22	36

DORMANCY

	2012	2013		2012	2013
MODIS 8-Day	-28	-43		-4	-1
Terra 16-Day	-43	-57		-20	0
Aqua 16-Day	-24	-11		-21	2
In-Situ Duration	187	139		166	144

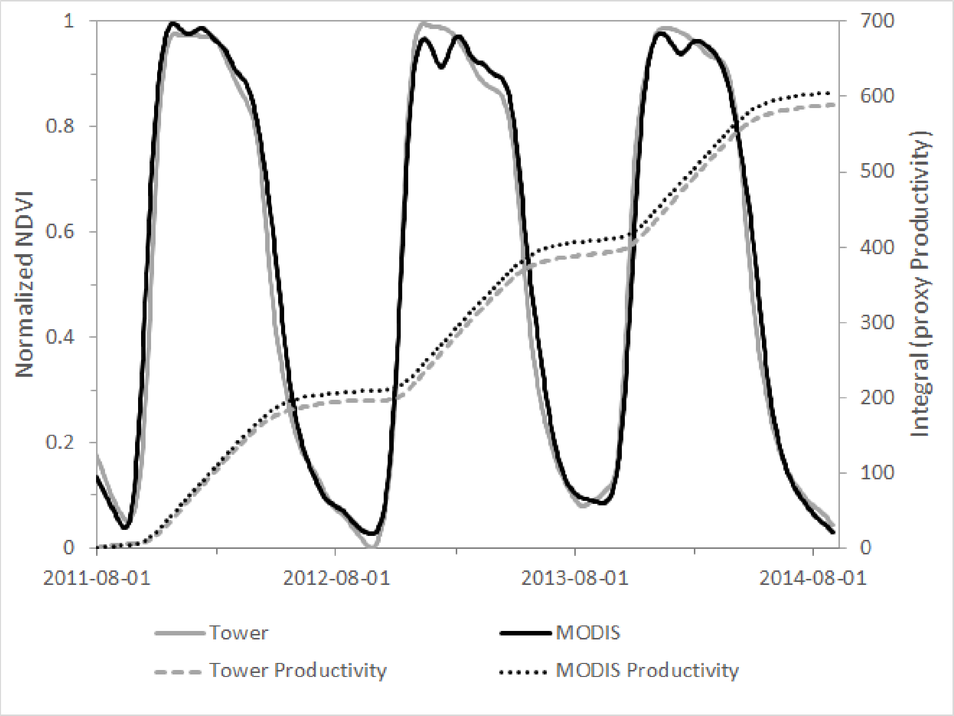
LENGTH OF GROWING SEASON M1

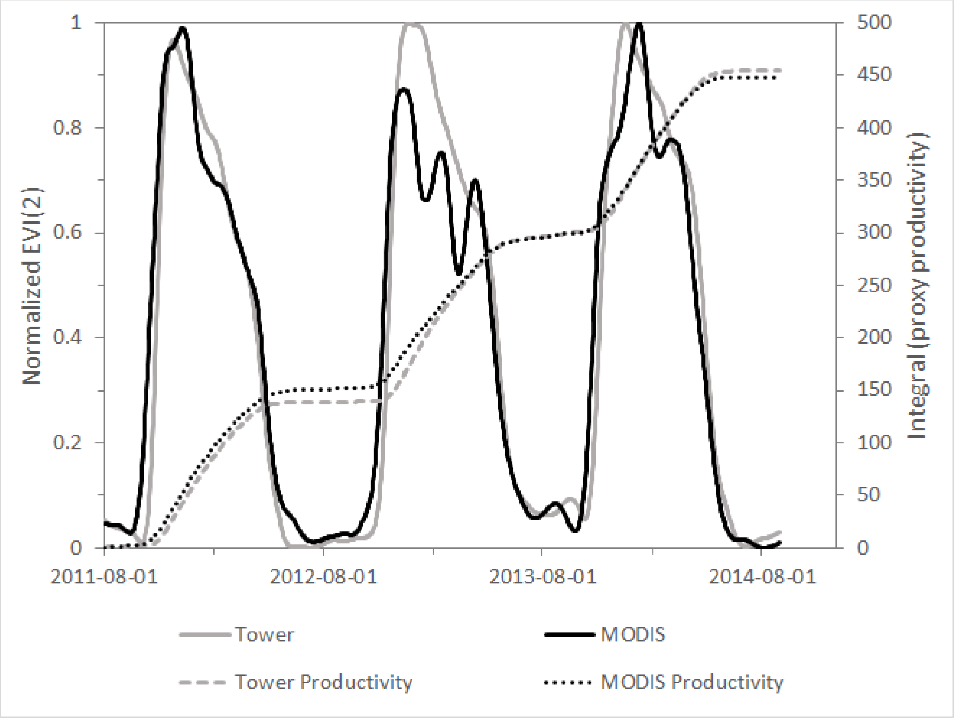
	2011-2012	2012-2013	2013-2014		2011-2012	2012-2013	2013-2014
MODIS 8-Day	31	-2	12		20	-5	-17
Terra 16-Day	23	20	16		28	15	-12
Aqua 16-Day	31	-5	13		9	-7	-19
In-Situ Duration	176	184	181		174	182	178

LENGTH OF GROWING SEASON M2

	2011-2012	2012-2013	2013-2014		2011-2012	2012-2013	2013-2014
MODIS 8-Day	36	49	25		1	1	25
Terra 16-Day	48	69	36		19	22	21
Aqua 16-Day	31	35	6		35	-10	21
In-Situ Duration	194	204	204		221	203	203

(FIGURE 4-8)


1
0.8
0.6
0.4
0.2
0
Normalized NDVI
700
600
500
400
300
200
100
0
Integral (proxy Productivity)
2011-08-01
2012-08-01
2013-08-01
2014-08-01
Tower
MODIS
Tower Productivity
MODIS Productivity


1
0.8
0.6
0.4
0.2
0
Normalized EVI(2)
500
450
400
350
300
250
200
150
100
50
0
Integral (proxy productivity)
2011-08-01
2012-08-01
2013-08-01
2014-08-01
Tower
MODIS
Tower Productivity
MODIS Productivity

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CHAPTER 5

SIGNIFICANCE, CONTRIBUTIONS & CONCLUSIONS

Earth observation from satellite remote sensing systems has revolutionized our holistic understanding of planetary geosphere-biosphere-atmosphere interactions in the last few decades. These sensor data are vital for mapping, monitoring, and modelling changes in forest biomes for sustainable management as we move into the Anthropocene epoch with unprecedented human population growth and rates of global environmental change (Naidoo et al. 2008; Sasaki and Putz 2009; Brewer 2012). Long term forest monitoring programs, with accurate understandings of the underlying physical principles that drive important biophysical processes such as photosynthesis, are necessary for developing predictive models of ecosystem resilience to disturbance and climate stress (Bonan 2008; Anderson et al. 2011). With an increasing number of vegetation monitoring satellites currently coming online there is a need for sensor and information cross calibration and in-situ validation to understand how to maintain long-term compatibility and accuracy of Earth observation time series. In order to overcome the limitations of satellite imagery researchers require tools that provide reliable, scalable ground reference information in difficult to access study sites (Baccini et al. 2007). Near-surface remote sensing platforms and wireless sensor networks are becoming more robust and practical for in-situ validation of satellite observations, offering high resolution information on dynamic forest processes at increasingly larger observation scales. The synergistic use of in-situ, airborne, and satellite sensors enables up-scaling and down-scaling of ecosystem process estimates with greater certainty than previously possible for remote sensing applications. The ability to expand our environmental monitoring from the micro to macro scale is critical to achieving well informed regional and global assessments of changes in forest ecosystem services.

Entering the information age of the 21st century, decision making for environmental management has the advantage of utilizing up-to-the-minute data on ecosystem health and performance using internet enabled measurement devices (Liang and Wu 2012). Near real-time data from remote off the grid locations can now be achieved using wireless internet connection and wireless sensor systems. While these sensor systems offer many advantages over traditional manual data collection methods, they can still be experimental for specific applications and unreliable for long term, self-sustaining operation. Development of robust, outdoor wireless sensor network technology and protocols for resilient, user-intuitive data collection systems is still needed for accessible use of WSNs in ecological sciences (Corke et al. 2010). Nonetheless, the use of information communication technology is becoming paramount for environmental monitoring and ecology research to obtain the sheer amount of data required to catalogue and understand the extent of modern global environmental changes (Tolle et al. 2011). Similarly, progressive cyber-database development is necessary to manage the volume of data being generated by these monitoring technologies, and maintain data provenance for experimental validation. The development of ad-hoc wireless sensor network hardware for data collection used in this thesis required the co-development of the Enviro-Net® cyber-database web infrastructure in order to manage the large amount of data produced by the sensor networks, and represents a new paradigm of environmental data collection, management, and provenance.

Tropical Dry Forests are unique ecosystems in the tropics as they are very strongly in tune with atmospheric conditions and can change drastically in appearance and performance from dormant, arid, leafless landscapes to lush, highly productive environments in a very short period of time. The responsiveness of TDF vegetation to changes in soil and atmospheric water content makes them ideal ecosystem level bio-indicators of climate change in the tropics. There is still a lot of debate in the scientific literature about whether climate change will affect the productivity of tropical forests as much as in higher latitudes, where temperature increases are already being seen to bring earlier spring leaf out and flowering dates in temperate plants (Menzel, et al. 2006). Korner and Basler (2010) describe how not all tree species in temperate forests respond to the same environmental drivers of leaf phenology, and that early and late succession species tend to differ in their bud-burst responses to changes in temperature and photoperiods. The relationship between tree species community assemblages, ecosystem succession, and phenological drivers has not been well studied in the tropics with respect to climate change and future variability in weather patterns. Feng et al. (2012) have identified current changes in rainfall seasonality in the tropics and warn that continued increases in inter-annual variability of seasonal timing and intensity of rainfall in the semi-arid tropics will have significant effects on regional and global biogeochemical cycles with implications for the livelihoods of local communities. With the current high rates of deforestation, reforestation, landscape fragmentation and secondary forest creation in the tropics it is important to understand how the interplay between succession, phenology and climate change will affect productivity and resilience of tropical forests, especially in seasonally dry environments where annual seedling survival and tree recruitment is already limited by drought severity.

Forest ecosystem phenology is a major driver of global annual exchanges of atmospheric carbon, and understanding how climate induced shifts in phenology is a significant limitation to our current ability to predict future climate regimes and terrestrial biosphere responses (Migliavacca et al. 2012). Wang et al. (2014) suggest that with global warming trends over the coming century, positive feedback forces between global temperature increases and drought in the tropics will cause a doubling of tropical forest carbon emissions. Their findings indicate that a single degree increase in mean temperatures corresponds to two billion more tons of carbon being released per year from tropical forests and savannahs, relative to the mid twentieth century emission response rates. This emphasizes the need for improved monitoring of tropical forest seasonality and succession processes and up-to-date information on forest health and ecosystem service performance. Such information can best be obtained using the synergistic application of satellite observation systems and internet-enabled terrestrial sensor networks for accurate, scale-able environmental informatics

RESEARCH CONTRIBUTIONS AND IMPLICATIONS FOR FUTURE WORK

The studies presented in this thesis are novel in their use of in-situ sensor networks for forestry science and progressive in the application of new technologies for ecosystem succession assessment in tropical forests. The results presented are, in part, intended to promote the use of environmental wireless sensor networks in forest monitoring applications and provide guidelines for improving sensor network performance in challenging and dynamic settings. Furthermore, the findings of tropical dry forest phenology patterns, climatic sensitivity, and microclimatic succession are intended to broaden our understanding of these processes for TDF management and conservation, as well as to be used as baseline measurements for future work evaluating forest productivity changes in the semi-arid agro-landscape of southeastern South America.

Chapter Two: *Seasonal Link Performance of a Wireless Sensor Network in Boreal Forest Phenology Monitoring*

Wireless sensor networks can be quick and easy to deploy in a forest environment since the user need not route hundreds of meters of cables through the forest understory. The majority of battery power consumption in a wireless sensor network is used up by the radio communications. Therefore, low power radio communication is vital to the success of a wireless sensor network. With low power signal transmission there are limitations to network communication distance. Chapter two explores the wireless signal strength variations of a 2.4 GHz spread spectrum direct sequence 40 mW sensor network signal using IEEE 802.15.4 packet delivery protocols in a seasonally deciduous boreal forest. This WSN communication protocol is one of the most commonly used in WSNs but has not been characterized in forest environments or with drastic seasonal changes in surrounding leaf area and climate. I demonstrate that the radio signal strength indicator (RSSI) does vary by a factor of ten during a full year of network operation due to surrounding environmental dynamics. Most of the short term variability in the signal was due to air and device temperature variations but the mean seasonal signal strength of the network was related most to the locally measured vegetation greenness indices. The results indicate that changes in forest leaf area index significantly affected WSN signal propagation, reducing data transfer success when the canopy leaf area increased. Relating forest phenology and weather patterns to WSN performance and data collection reliability introduces a new level of understanding in this emerging environmental sensing technology and improves our ability to design monitoring networks to become more autonomous and reliable in challenging environments like forests.

Chapter Three: *Seasonality and Succession and of a Brazilian Tropical Dry Forest: Phenology and Climate Moderation in Secondary Stands*

Conservation of Tropical Dry Forests (TDFs) in the Americas requires a better understanding of secondary succession processes in the context of natural regeneration, climate sensitivity, and ecosystem service assessment. As rainfall patterns are expected to change in the semi-arid tropics (Feng et al. 2012), climate change researchers require empirical data to constrain global dynamic vegetation models (DGVM) to decrease uncertainties in climate-biosphere feedback forecasting. Data on meteorological drivers of TDF ecosystems phenology can be used to constrain DGVMs and improve our understanding of changing drought regimes on TDF productivity and related ecosystem services. Chapter three contributes several relevant ideas in this context: first, that a significant drop in atmospheric vapour pressure deficit (VPD) always accompanies the start of the forest green-up, that there may be a dry season rainfall threshold of 100 mm or more required to initiate leaf bud burst, that a time lag of 10-15 days is needed after this rainfall threshold for full canopy leaf expansion, and that soil water content explains the majority of seasonal changes in canopy NDVI and EVI in a continental Brazilian TDF. In addition, younger TDF canopies appear to be more sensitive to mid-season drought by exhibiting greater sub-seasonal changes in vegetation greenness and fAPAR than older growth forest stands. In relation to these findings, more work needs to be done to relate remotely sensed (near or far) leaf area index and vegetation greenness indices to photosynthetic phenology patterns so that carbon dioxide fluxes can be linked to changes in canopy biophysical dynamics in order to accurately assess temporal fluctuations in carbon source or sink contributions of secondary TDFs.

Secondary TDFs can recover biomass quickly, depending on prior land use intensity, but species composition of an old growth secondary TDF often differs from primary TDF composition. The drivers of community succession are not well understood but are thought to be related to abiotic resource competition more so than in moist tropical forests due to the severe dry season each year limiting seedling and sapling survival (Vieira and Scariot, 2008). As secondary vegetation succeeds in a young TDF the generation of microclimate diversity is important for the establishment and co-existence of different tree species. The results presented in chapter three contribute to the knowledge base on understory microclimate generation and diversity during secondary succession, revealing the extremes of VPD and temperature during drought periods. All of the high frequency, long-term micrometeorological data collected and used in this study is made available on the Enviro-Net® web portal for further investigations (www.enviro-net.org). In addition, I report on the canopy climate moderation of a young and old growth secondary TDF and how they relate to seasonal changes in canopy leaf area and water availability. The data suggests that old growth secondary TDFs are significantly better at moderating understory temperatures and dryness than early stage forests. The quantification of these extreme drought and heat moderation capacities of TDF canopies is to be referenced as an ecosystem service provision for conservation frameworks that consider indirect climate moderation benefits of TDFs.

Chapter Four: *Evaluating MODIS Vegetation Indices for Monitoring Tropical Dry Forest Phenology across a Successional Gradient using Optical Phenology Towers*

Vegetation phenology is a fundamentally important process to the global carbon cycle controlling land surface atmospheric fluxes of energy and gases. Since tropical forests contain the majority of above ground biomass on Earth and can contribute large fluxes of carbon dioxide to the atmosphere during drought periods, tropical deciduous forest leaf phenology is worthy of in-depth monitoring and assessment with respect to climate change. Precise measurements of forest leaf seasonality are required for the evaluation of shifts in phenological timing that reflect inter-annual changes in ecosystem productivity. Satellite optical remote sensing of phenology in the tropics is challenging due to the frequent limitations of land surface visibility from space and can be biased by data availability (Huete and Saleska, 2010). Near-surface optical remote sensing of phenology from tower platforms can overcome these limitations and provides continuous hyper-temporal canopy state observations, but only offers small scale, plot level information on canopy phenology. Chapter four focuses on the comparison of the in-situ optical phenology to phenology observation derived from MODIS satellite products for validation of remotely sensed seasonality parameters in a tropical dry forest. The results indicate large differences between the two phenology time series, both in absolute scales and with regards to growing season start and end dates. More work needs to be done to understand the causes of these disagreements but the most likely reason is the data aggregation process for MODIS composite NDVI and EVI products. Therefore, it is recommended that MODIS users do not use these products for assessing shifts in TDF phenology in association with climate driven changes in semi-arid tropical productivity, or to include extensive ground validation work using near-surface sensing systems when attempting such studies.

We also conclude that TDF phenology observed across four plots representing a 50 year successional chronosequence demonstrates very few differences between the timing of growing season and dormancy onset. However, younger successional stages TDF stands had less stable canopies throughout the growing season, particularly during the second half of the growing season when precipitation becomes less frequent. These findings suggest that abiotic environmental drivers are more important than community assemblage biotic drivers for canopy phenology patterns in the TDF study region. In addition, early stage secondary TDF canopies may be more affected by periods of mid-season droughts, reducing photosynthetic rates more than late stage trees, despite often having more pioneer tree species that are typically considered more drought resistant. Future work investigating the effect of mid-season drought on species specific mortality and stand age mortality rates in secondary TDFs would improve our understanding of TDF resilience to climate change in the Neotropics.

OVERALL SIGNIFICANCE

The results and findings of the studies in this thesis are to be used to broaden the knowledge regarding Neotropical dry forest regeneration sciences and bring to light the concepts of phenology monitoring and microclimatic succession as relevant conservation research parameters. Furthermore, the show that the use of satellite remote sensing for forest resilience and productivity change detection should be complimented by near-surface optical sensing and wireless sensor network technologies to improve the accuracy and scalability of information on forest biophysical dynamics. As deforestation continues to be a problem in the tropics and secondary tropical forests offer the potential for climate change mitigation, our ability to assess forest conservation and regeneration efforts rely on advances in scientific tools for rapid and reliable evaluation of ecosystem dynamics. I hope that the concepts and methodologies presented here will be valuable contribution to Earth observation sciences and sustainable forestry practices.

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