1-1-2017

Exploring Historical Coffee and Climate Relations in Southern Guatemala: An Integration of Tree Ring Analysis and Remote Sensing Data

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Abstract

This dissertation makes use of a physical geography perspective to examine the relationship between agriculture and climate in Guatemala using dendrochronology. I examined the potential of high-resolution climate proxy data from dendrochronology to help fill in the gaps of past climate information to better understand the natural and anthropogenic variability of precipitation which, in turn, can inform Guatemala's agriculture sector. This research has demonstrated successful cross-dating and climate sensitivity of *Abies guatemalensis* in the Pacific slope of Guatemala. Based on this, I have produced a 124-year record of mean precipitation from June-July-August. The mean precipitation from June-July-August at this site seems to receive an important influence from the sea surface temperature (SST) in the Pacific Ocean in the form of El Niño Southern Oscillation (ENSO) in the region 3.4. The analysis on the frequency of the precipitation records suggests that single year droughts dominate the record yet, periods of 9 years below-average rainfall can persist. Likewise, single year pluvial events also dominate the evaluated period. The long-term reconstruction of precipitation allowed to describe past relationships between coffee plantations and pests. For instance, the frequency analysis suggests that 4 or more consecutive periods of above-average precipitation are associated with several coffee pests and subsequently great economical losses due to crop failures, including the last coffee leaf rust crisis.

This study also presents a streamflow reconstruction of the Upper Samalá River watershed using a tree ring-width chronology derived from the Guatemalan fir (*Abies guatemalensis*) to reconstruct mean August-September-October streamflow volumes for the period 1889-2013. Our analysis shows that strong statistical correlations are present between tree-ring width measurements and monthly natural streamflow series. The mean August-September-October streamflow variability is dominated by single year events for both above and below the long-term mean. This reconstruction reveals important teleconnections with the ENSO 3.4 region and it is to our knowledge, the only streamflow reconstruction in Guatemala using tree-ring measurements. This new long-term record will be useful to recalculate historical discharge peaks and floods that affect agricultural areas in the mid and lower basin but also the hydroelectric production.

Our analysis suggests that records from the GIMMS 3g v.0 Normalized Difference Vegetation Index (NDVI), are inversely correlated to precipitation in the Upper Samalá River watershed at the location of the *A. guatemalensis* forest stand Kanchej. This suggest that the net solar radiation income during the cloud-free timing throughout the mid-summer drought could be partially responsible for promoting cloudiness by heating the SST and hence, promoting precipitation during the second peak of precipitation during September and October. The independent analyses of precipitation and NDVI sensitivity of *A. guatemalensis* and the correlation between precipitation and NDVI suggest that precipitation is a modulator of radial growth of *A. guatemalensis* in this location of Guatemala. These findings can be used to refine the knowledge on the climatic controls on *A. guatemalensis* radial growth.

Document Type

Dissertation

Degree Name

Ph.D.

Department

Geography

First Advisor
Matthew J. Taylor, Ph.D.

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Keywords
Climate change, Coffee, Dendrochronology, Guatemala, Hydroclimatic reconstruction, Paleoclimatology

Subject Categories
Forest Sciences | Plant Sciences

EXPLORING HISTORICAL COFFEE AND CLIMATE RELATIONS IN SOUTHERN GUATEMALA: AN INTEGRATION OF TREE RING ANALYSIS AND REMOTE SENSING DATA

A Dissertation

Presented to

the Faculty of Natural Sciences and Mathematics

University of Denver

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

By

Diego Pons

August 2017

Advisor: Matthew Taylor

Author: Diego Pons
Title: EXPLORING HISTORICAL COFFEE AND CLIMATE RELATIONS IN SOUTHERN GUATEMALA: AN INTEGRATION OF TREE RING ANALYSIS AND REMOTE SENSING DATA
Advisor: Matthew Taylor
Degree Date: August 2017

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ACKNOWLEDGEMENTS

This research was possible only because of the adventurous and brave spirit of incredible friends who spent months in the forests of Guatemala under difficult conditions at times, but always believing in the importance of what was being done. I want to thank the hospitality and support of Doña Enriqueta Salanic and Don Ramón Rixquiajqué, community leaders of La Estancia, Cantel. I am especially grateful with the information provided by the National Weather Association (INSIVUMEH) and the National Coffee Association (ANACAFE), especially to Florencio Pappa, Keben Delgado and Mariela Meléndez. I very much appreciate the reviews of the manuscript from Shane Neeley and Edwin Castellanos. I am grateful with the Fulbright grant and the people behind it. It changed my life. I also appreciate the funds provided by NSF to support this research. I'm grateful for the support from my committee who believed in the project from the beginning. Finally, I want to acknowledge the support from my parents, my sisters and my supportive partner Sydney Neeley. Without your support this wouldn't have been possible.

D. P.

Denver, Colorado

August, 2017

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PREFACE

This dissertation makes use of a physical geography perspective to examine the relationship between agriculture and climate in Guatemala using dendrochronology. To do so, I have picked the most iconic and economically important crop of Guatemala, Coffee. Not only is this crop currently facing climate-related challenges, but uncertainties regarding future hydroclimate prevent farmers from making well-informed decisions regarding adaptation strategies. Several future climate scenarios for Guatemala project large negative impacts on coffee productivity, but these models are based on coarse data. I argue in this dissertation that a way to better understand the potential effects of climate variability on coffee productivity is to look back into past hydroclimate to better inform predictions of the future. By learning about past hydroclimatic variability and the impact it has had on coffee, we can also incorporate knowledge on practical constraints and alternative courses of action put in place during previous experiences with climate extremes on coffee plantations. This allows for instance to evaluate the past climate during historical coffee crises related for example to pests and infestations. However, this venue of research cannot be developed with the current scarce instrumental data available for the country, which extends only for around 47 years into the past. Here, I examine the potential of dendroclimatology to extended the record of hydroclimatic variability that can then be linked to on-the-ground experience lived by coffee farmers in the country in previous weather-extreme conditions.

Coffee is grown in virtually all the mountainous regions of Guatemala and the past impacts of climate variability have affected coffee growing regions in diverse, sometimes opposite ways. I have chosen to focus in a location that represents an important sector of the coffee productivity of Guatemala where 60% of the total coffee is produced: the southern mountainous region. There, farmers have historically dealt with market shocks, climate extremes, and pests. These factors -the most important stressors for coffee farmers in Guatemala- interact and modulate the productivity of coffee farms in this location. However, the short span and coarse resolution of climate data for Guatemala, limits our capacity to explore the influence and interactions of climate with the market and pests and infestations. Without understanding the past influence and interactions of climate variability on coffee productivity, adaptation strategies suggested by policy makers are merely exploratory and the outcomes of such actions highly uncertain. Moreover, policy-making based on climate trends analysis based on limited climate records could be misleading. I have chosen to work with the coffee farmers within the Samalá Watershed organized in an association (PALAJUNOJ), where the need for climate information upon which they can act in the face of changing climate has been recognized as an urgent adaptation strategy. Despite the focus on Coffee (*Coffea arabica*) in this study, the climate reconstruction generated here can be used by many other agriculturalists in the region by transforming the new climate data into comprehensive information specific to other crops. The last part of the dissertation makes us of satellite-derived vegetation indices to evaluate photosynthetic activity, tree-ring growth and climate interactions near coffee plantations. Although the hydrocimate record produced here goes back 124 years, future research could extend this record back to at least 1780.

CHAPTER ONE

INTRODUCTION

Coffee is the second most traded commodity after oil (Bernades et al., 2012). International coffee trade generates over US$ 90 billion each year and supports the livelihoods of 100 million people worldwide (Pendergast 1999; DaMatta & Ramalho 2006). Smallholder family farmers produce over 70% of the world's coffee in 85 countries in Latin America, Asia, and Africa (Oxfam 2001). Most coffee producers live in poverty and manage agroecosystems in some of the most culturally and biologically diverse regions of the world (Bacon 2005; UNFCCC 2007). In Central America coffee is the most economically important crop, reaching a value of $3.70B in 2011 (Imbach et al., 2017). A reliance on coffee production comes with many challenges because the coffee crop is very sensitive to climate changes (Hannah et al., 2017). This has raised concerns for the coffee production industry because Central America is expected to experience disproportionate agricultural impacts from climate changes over the next decades (Giorgi 2006; Hannah el at., 2017; Imbach et al., 2017). However, there is high uncertainty related to the potential effects of these climate changes on coffee production mainly because historical records of climate change in the Central American region are fragmentary limiting the current trend analysis only back to 1960 (Hannah et al., 2017). Because of this uncertainty, an in-depth examination into the past effects of climate variability and extremes on coffee production could inform future relationships between coffee and climate in Guatemala. This is needed for many reasons. First and foremost, half of Guatemala's population live in rural areas and rely on agriculture to meet their daily needs (Aguilar-Støen et al., 2014). Among various agricultural products, coffee is the backbone of thousands of families' livelihoods (Steinberg et al., 2014). Secondly, the country is among the ten largest coffee exporters of the world (ITC 2011). Coffee is planted on 753,671 acres ranging from 600 m.a.s.l. to 2,000 m.a.s.l and involves about 125,000 farmers (ANACAFE 2017). And thirdly, there are an estimated 700,000 people economically dependent on coffee (Tucker et al., 2010). Coffee remains one of Guatemala's most important economic resources, representing up to 13% of the GDP, therefore a loss of production due to climate changes could have devastating socio-economic and ecological consequences, including the loss of several ecosystem services (World Bank 2011; Schmitt-Harsh 2013).

Framework, Methods and Literature Review

Coffee is grown in virtually all the mountainous regions of Guatemala from 600 to 2,000 m.a.s.l., where the impacts of past climate variability have affected them in diverse ways (CIAT 2012). For instance in 2006, during a spell of precipitation extremes that affected Guatemala's coffee productivity, half of the coffee farmers interviewed in a study by Castellanos et al., (2010) reported crop losses due to excessive rainfall while the other half reported the cause to be lack of rain. Because of the spatial variability of the climate impacts on coffee productivity, I have chosen to focus in a single region that represents the most important sector of the coffee productivity of Guatemala, the Pacific mountainous region. There, 60% of Guatemala's coffee is produced from 600 m.a.s.l. to

2,000 m.a.s.l. (ANACAFE 2017). However, similar to other coffee producing regions of Guatemala, the influence of a given climate phenomenon in the Pacific basin of Guatemala (e.g. El Niño Southern Oscillation, herein ENSO), can have divergent effects on the coffee productivity of the region. For instance, the National Coffee Association of Guatemala (ANACAFE) reported in 2015 that the 2009-2010 positive phase of ENSO, had increased coffee productivity in the western side of the Pacific mountainous regions up to 24% while the eastern side reported a loss of 22% on the total coffee productivity. Due to this spatial variability of the climate impacts on the region, I decided to focus on a single watershed to delimit the study area. The watershed approach has been recognized as an adequate way to assess the hydroclimatic factors (Molle 2009; Moss & Newing 2010). Hence, I selected the Samalá River watershed.

The site selection was also based in an opportune arrangement of factors. For instance, the Guatemalan Fir (*Abies guatemanlensis*) has demonstrated reliable cross-dating, sensitivity to climate (Anchukaitis et al., 2013) and has been successfully used to reconstruct precipitation in the western highlands of Guatemala (Anchukaitis et al., 2014). The natural distribution of the *Abies guatemaslensis* in the upper part of the Samalá River watershed was described by Andersen et al 2006, and resulted in a convenient location to assess its climate sensitivity (see Appendix A). The forest, which became a protected area in 1995, is well-known to the communities of Zunil, who co-manage it for both conservation and timber harvesting (De Urioste-Stone et al., 2013). The name of the forest in local K´iché language is Kanchej. It is located in the upper Samalá River watershed which covers 1,500 km² across the departments of Quetzaltenango, Retalhuleu and Suchitepéquez (Figure 1.1). Located between

Santiaguito and Santo Tomas volcanoes, it follows the Zunil Fault Zone to the south (Bennati et al., 2011).

Figure 1.1. Study location in southern Guatemala. The Samalá River Watershed is highlighted. Sampling location is indicated by a green star located at 14°46'39.68"N, 91°26'17.94"W at 3,300 m.a.s.l. and coffee growing areas are emphasized in gray. Source: Pons et al., 2017.

Climatic characteristics of the study area

The average annual precipitation within the watershed ranges from around 2,000 mm at the high elevations and along the coast to about 5,500 mm near the middle altitudes of around 630 m.a.s.l., probably due to a rain-shadow effect. The average annual temperature ranges from 10ºC at the highest elevation to 25.5ºC on the coastal planes (MAGA 2002). The closest instrumental records for the study are recorded by the

Labor Ovalle and Zunil weather stations which are managed by the National Weather Institute (INSIVUMEH) and the INDE (National Electrification Institute of Guatemala) respectively in Quetzaltenango and Zunil. The precipitation record from this station begins in 1980 (Labor Ovalle) and temperature begins in 1982 (Zunil). The precipitation dataset has no missing values, however the temperature dataset from the Zunil weather station presented a few missing values (11%) in the record. These missing values were filled using the approach suggested by Pappas et al., (2014), which suggests the use of time-adjacent observations to obtain a local mean using one observation before and one after the missing value. The annual distribution of precipitation and temperature is presented in figure 1.2, where a bimodal distribution of precipitation can be observed.

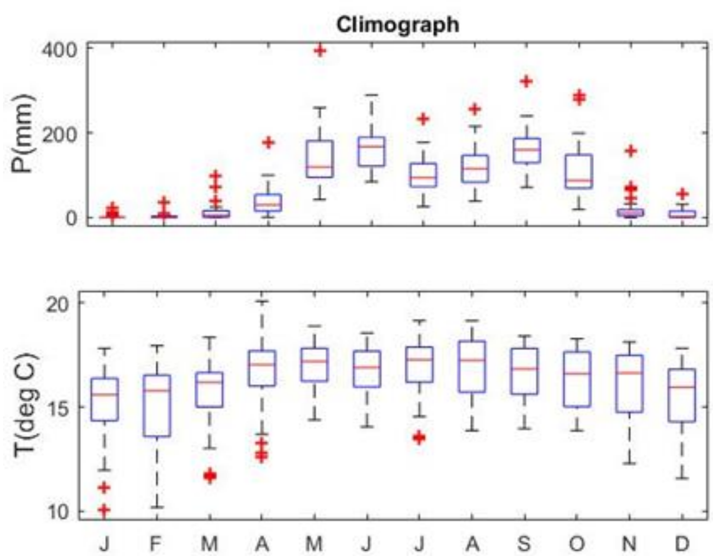

Figure 1.2. Monthly distribution analysis of climatological records from instrumental data from Labor Ovalle (precipitation) and Zunil weather station (temperature) for the period 1982-2013 Source: INSIVUMEH 2017/ INDE 2017.

The historical suitable agro-ecological conditions that include marked rain seasonality (Magaña et al., 1999) and volcanic soils have made the Pacific slope of Guatemala an optimal location for agriculture where coffee still represents one of the most important crops (Clarence-Smith, W. G.; Topik, Steven 2003; Finegan and Bouroncle 2008). However, the mechanisms behind certain precipitation regimes like the mid-summer drought shown in the aboce image during July-August are not fully understood (Magaña et al, 1999; Rauscher et al., 2008), limiting our ability to forecast these events that remain critical for agriculture in the region.

Coffee and Climate in Guatemala

Aside from market-related shocks, the most significant threat to the future of coffee production in Guatemala is related to the uncertainties of future climate, especially hydrological variability in the form of precipitation extremes (Tucker et al., 2010; Hanna et al., 2017). The reason for this is that at least three aspects of flowering phenology (onset, density and frequency) are influenced by the amount and timing of precipitation (Peters & Carroll 2012) and have a direct effect on coffee productivity. On the other hand, temperature increases have been reported in the mountain regions of Guatemala where coffee is planted, including the Pacific mountainous regions (Pons et al., 2017), which seems to follows projections from models for the region (Karmalkar & Bradley 2011; INSIVUMEH 2016). However, climate simulations for precipitation in these regions tend to underestimate precipitation, and fail to represent the regional topographical features that modulate rainfall events (Rauscher et al., 2008; Karmalkar et al., 2011). Hence, the uncertainties associated to future climate models on precipitation for the region remain high, limiting our understanding of future precipitation/temperature interactions.

When it comes to agriculture, precipitation changes and temperature should not be assessed separately, because increasing temperatures will likely have an effect on evapotranspiration and therefore on coffee productivity. Our understanding of past and future precipitation variability and change in tropical regions like Guatemala has proven to be limited, leaving coffee farmers with great uncertainties regarding the adequate adaptation schemes (Karmalkar et al., 2011; Hannah et al., 2017; Pons et al., 2017). In addition, current precipitation data throughout Central American is described by highly spatially variable records and statistically insignificant trends usually dependent on the data set used (Aguilar et al., 2005; Neelin et al., 2006; Hannah et al., 2017) which complicates the understanding of the interactions between the market, the climate and pests and infestations, which remain the main stressors for coffee producers in Guatemala.

Coarse spatial resolution and high uncertainties associated with the models for precipitation in Central America suggest that the whole range of precipitation variability at a regional and local scale is not well understood (Aguilar et al., 2005; Alexander et al., 2006; Karmalkar 2010; Karmalkar & Bradley 2011; Jones et al., 2016; Hannah et al., 2017; Rauscher et al.,2008). The lack of instrumental data and the uncertainties in climate models regarding future precipitation in Guatemala could harm agricultural productivity because the knowledge on timing and quantity of rainfall is critical to the management of many crops, including coffee (Pons et al., 2017).

Detailed regional climate information (both historical and projected) is necessary to develop policies that can lead to improved adaptation strategies to climate changes

(Donatti et al., 2017). However, according to the IPCC AR 5 (IPCC 2013), the lack of adequate regional climate data still limits climate adaptation and vulnerability reduction in Africa, Asia and parts of the Americas. In Guatemala, the coarse spatial resolution of the climate models and low density of weather stations limits our ability to fully characterize climate change and variability, and therefore to derive policies that may be useful for local or regional adaptation strategies. With regards to climate proxies, the lack of climate reconstructions outside of Mexico still restricts the southern extent of precipitation reconstructions (Anchukaitis et al., 2014). These gaps in the reconstructions of precipitation extremes limit the support of regional climate assessments. This is critical knowledge for the risk management at the Samalá watershed because hydro-meteorological catastrophes are the most frequent type of disasters in the watershed (Soto 2015).

The role of dendrochronology in building historical climate knowledge

Reconstructing historical climate knowledge at a regional and local scale is important for many reasons. For instance, when long instrumental records are not available and the low-resolution of the GCMs limits the assessment of climate at regional scales, climate proxies such as tree-rings width can be used to estimate past precipitation or temperature variability (Anchukaitis et al., 2013; IPCC AR5 2013). An extended record of past climate is of utmost importance in vulnerable, agriculture-dependent locations because it can be used to evaluate trends, inform on previous courses of action related to weather extremes and pest. Aside from these advantages, a local climate record is also important because most of the knowledge on climate variability in agricultural locations is bases on local perceptions (Brondizio & Moran 2008), and when forecasts bases on coarse resolution sources contradict local experience this can jeopardize the trust in newly generated scientific knowledge and may lead to little change over agricultural practices towards at best and to misleading adaptation strategies at worst (Cash et al.,2003). In the case of the Pacific mountainous region of Guatemala where coffee is grown, a regional policy recommendation based on limited knowledge of ENSO variability and its impact on different sides of the mountain where coffee is produced could be misleading to the farmers on different locations of the same mountain.

On the other hand, Brondizio & Moran (2008) found that when historical records are missing, farmers' memories of climate events decreased significantly after 3 years (e.g. droughts), which impacted the sense of "direction" of the local climate trends (direction meaning the awareness of, for example, increased frequency of droughts). This lack of sense of climate trends could have an impact on the urgency to act upon climate variability. Another advantage of locally reconstructed climate history is that the information generated by it can be transformed into agrometeorological information, which means that the linkage between physical and biological parameters of locally grown crops can be established and then the climate information becomes comprehensive for the stakeholders (Sivakumar 2006).

In addition to these local advantages, the longer climate record provided by dendrochronology can add to the understanding of broader climate processes, reduce climate gaps due to the shortage of meteorological stations and serve to verify General Circulation Models (GCMs), and regional climate models (RCMs), by providing information of local variability (Beniston 2002; Taylor et al., 2012). This is of particular usefulness in the mountainous regions of Guatemala where instrumental data is scarce (Pons et al., 2017; Karmalkar et al., 2011) and where historical suitable agro-ecological conditions that include marked rain seasonality are changing (Clarence-Smith, W. G.; Topik, Steven 2003; Finegan and Bouroncle 2008). The ability to predict changes in precipitation patterns and trends and understanding past effects of precipitation extremes on coffee productivity is critical because precipitation variability in the Pacific slope of Guatemala translates into droughts, increased precipitation, and floods that have the largest impacts on the coffee crop, among a vast number of other crops in the region including banana and vegetables (Soto et al., 2015; Imbach et al., 2017).

In this study I build on the previous successful precipitation reconstruction using *Abies guatemalensis* in Guatemala by Anchukaitis et al., (2014) to explore the potential of this species to expand the precipitation records on the Pacific slope of Guatemala. I also evaluate the use of different climate datasets used to calibrate and validate the reconstruction models in regions with limited instrumental data. I assess the potential of the *A. guatemalensis* chronology to reconstruct the streamflow from the upper Samalá River basin. I explore the relationships between the chronology, climate, and satellite-derived Normalized Difference Vegetation Index to explore potential responses to inform on the cambial and leaf activity. This is as a first step to assess the viability of using satellite imagery to estimate Net Productivity Production (NPP) and Gross Productivity Prodcution (GPP) using on-the-ground estimations of biomass. Finally, I incorporate notions of climate information co-production described in previous work in Guatemala where new insights on this complex processes are discussed.

Content

The different components of the hydroclimatic reconstruction presented here have been developed within the same study area with the intention of covering as much as possible the interconnectivity between the different aspects of the hydrological processes and their influence on coffee productivity. However, the chapters are intended to be publishable units and made available to stakeholders in Guatemala after a peer-reviewed process. Therefore they appear as independent research studies. Because of the common ground of the theory and methods behind the hydroclimatic reconstruction, some overlap between the successive chapters is presented. This allows the reader to navigate through the dissertation with previous knowledge and a sense of the implications of these on the following chapter.

Chapter Two introduces the reader to a review of the different broad climate mechanisms that interact to generate the climate conditions in Central America, including the associated uncertainties and future research venues. Therefore, it also points to the need of more studies that could led to a better understanding of these mechanisms, their interactions and their influence over the Central American domain. The potential of dendrochronology to alleviate the gaps of information is discussed. Chapter Three is intended to expose the reader to the different climate sensitivities of coffee (*Coffea Arabica*) to highlight the impact of weather extremes and climate change on coffee plantations. It points to the difficulties of growing coffee in Guatemala with market shocks, climate variability and coffee pests and diseases and the interactions among them. It describes how these processes are exacerbating the already difficult enterprise of growing coffee and how they can impact future coffee productivity in Guatemala. Chapter Four represents the base upon which the subsequent chapters are built on. Hence, it is the most important chapter because it demonstrates a successful reconstruction of precipitation using dendrochronology. It adds to successful dendrochronological studies from Anchukaitis et al., (2013, and 2014) in the region and complements our understanding of the influence of climate over the Guatemala. This chapter also emphasizes the usefulness of past instrumental records to validate climate reconstructions using dendrochronology and evaluates the usefulness of different climate records (e.g. instrumental and gridded data) used to assess the climate sensitivity of a chronology. Chapter Five delves deeper into the potential of dendrochronology to reconstruct other hydroclimatic features. It builds on the theory, methods and results from the previous chapter to demonstrate a multidecadal streamflow reconstruction of the Upper Samalá River. The new long-term record of streamflow could help recalculate the current high and low historical peaks. The frequency of above and below-average streamflow, relevant to agriculture and hydroelectric production, is analyzed. The relationships between streamflow and lahar events within the Samalá watershed and their impact on coffee is explored. Chapter Six evaluates the potential of combining dendrochronology and satellite derived imagery to refine our knowledge on the climatic sensitivity of *Abies guatemalensis*. This chapter explores the combination of these methods as a first step to develop a long-term ecosystem productivity record that could potentially be used for adjacent agricultural plantations like coffee and for carbon sequestration estimations. The implications of our findings to climate understanding are highlighted. Chapter Seven summarizes my findings and discusses their usability under a co-production paradigm.

CHAPTER TWO

CLIMATE MECHANISMS IN COFFEE-PRODUCING COUNTRIES IN CENTRAL AMERICA

The basic features of climate and weather in Central America and the Caribbean have been relatively well-known since the mid 1960's (Hastenrath, 1966). The dry season for the region, present during the boreal winter, is dictated by the southernmost position of the inter-tropical convergence zone (ITCZ). The wet season follows the northward position of the ITCZ for the boreal summer from May to October with a dry spell during July-August known as the mid-summer drought (MSD) or *canicula* (Hastenrath 1976; Magaña et al 1999; Polzin et al., 2015). This bimodal precipitation function can be drawn for most of the Central American and Caribbean region yet, the mechanisms behind the MSD are not fully understood (Rauscher et al., 2008). Although variable across the region, convectional precipitation has been associated with warm surface waters, low pressure and weak low-level subsidence on the Caribbean/Atlantic side (trade winds) and strong southerlies on the Pacific side (Hastenrath & Polzin 2013). The direct radiation from the sun at low latitudes seems to be the main driver for convectional precipitation along the ITCZ but also continentality plays an important role on modulating the actual position of the convergence. Hence, the interaction of the South American continental mass plays an important role in determining the position of the ITCZ by interaction with on-land temperatures, especially during boreal winter.

Recently, the influence of other ocean-atmosphere mechanisms acting on the precipitation and temperature of the tropics has been increasingly acknowledged (Hastenrath 2002; Chang et al., 2006). For instance, the interactions between the ITCZ position, the North Atlantic Subtropical High (NASH), the North Atlantic Oscillation (NAO), the Western Hemisphere Warm Pool (WHWP) and ENSO have been subject of study because these interactions are of particular importance for the Central American region climate (Hannah et al., 2017). Yet, the need for further research is suggested across the literature concerning the understanding of these interactions (Rauscher et al., 2011; Taylor et al., 2011). Because of this, the potential responses of some of these systems to global warming –especially those associated to precipitation- are also not yet clearly understood making it the main focus of this study (e.g. Li et al., 2011; Hannah et al., 2017).

Orographic precipitation

Aside from convectional rainfall generated by the warming of the oceans, orographic precipitation plays an important role on the accumulated annual precipitation in Central America (Karmalkar et al., 2011; Rauscher et al., 2008). This horizontal precipitation interacts with the complex mountainous regions of Central America to create precipitation during both the dry and wet seasons. The arrangement of the precipitation and surface air temperature (SAT) by territories has been assessed by Karmalkar et al., (2011), to show the effect of topography as a modulator of these variables across

Mesoamerica. The most influential feature of this mechanism is the cordilleras in most of the territory that divides the isthmus into the Caribbean/Atlantic and Pacific basins, at least for tropospheric winds and moisture. These cordilleras might also add complexity to the interpretation of gridded weather station data and CGM's skills as discussed in further chapters.

The North Atlantic Subtropical High

The precipitation in Central America has been mainly associated with the position of the ITCZ as described before yet, the North Atlantic Subtropical High (NASH) can have an influence on the precipitation regimes in the region through the decrease/increase of the trade winds. Overall, high sea level pressure (SLP) from the NASH domain promotes stronger trade winds, cooler SST and therefore less precipitation (Giannini et al., 2001; Taylor et al., 2011). Aside from a south-north motion of the NASH during the boreal summer (Hastenrath 1976), it also shows a westward expansion during July-August (Li et al., 2011; Polzin et al., 2015) which has an influence on the mid-summer drought or *canicula*. These dry spells can last from 5 to 15 days (Polzin et al., 2015). The anomalous descending (SLP) and increased low-level flow created by the influence of NASH through stronger trade winds also interacts with the ITCZ during the early part of the rainy season by weakening convection (Rauscher et al., 2011).

Caribbean Low-Level Jet

The moisture carried mostly by the trade winds over the Caribbean side of Mesoamerica is vital for large-scale water budget and ecosystems in the region

(Hastenrath 1976, Karmalkar et al., 2011). The trade winds develop into the Caribbean Low-Level Jet (CLLJ) in the Atlantic basin and have proven sensitive to several of the mechanisms described above, especially to the incursion of the NASH into a westward position and El Niño Southern Oscillation (ENSO) events. The NASH and the ENSO processes could have a similar influence on the CLLJ because they both seem to promote an increase of the NE surface winds, yet the mechanisms behind the two processes are different. The westward position of the NASH has been related to big-scale anthropogenic warming processes and an extension of the high-pressure ridge into the Caribbean and Gulf of Mexico (Li et al., 2011), while the ENSO acts on the CLLJ by changing the Walker circulation and therefore also increasing subsidence into the Caribbean. Yet, the overall interactions between ENSO and the NASH mechanisms requires further research (Diaz et al., 2001, Gouirand et al., 2014).

Higher rainfall in the Caribbean basin has been related to warm sea surface temperatures (SST), reduced sea level pressure (SLP) and weakened trade winds (Taylor et al., 2011). Therefore, any changes in the SST and SLP can have an influence on the intensity of the trade winds and subsequently on precipitation. This is a complicated process because the SLP associated with the NASH and the convergence associated to the ITCZ or Walker circulation from the ENSO can have an influence on the meridional pressure gradient at low latitudes. This in turn can influence the atmospheric circulation of the trade winds subsequently affecting the low surface flow over the region (Giannini et al., 2000).

Overall, the CLLJ is characterized by strong low-level winds with peaks during February and July. According to Taylor et al., (2011), the CLLJ acts as a modulator of the midsummer drought by providing orographic rainfall on the Caribbean basin during July-August, the months where subsidence in the Caribbean contrast the ascending air masses in May-June and September-October (Poltzin et al., 2015). This hypothesis supports the idea that the processes generating the bimodal precipitation -that is the peaks in May/June and Sept/October in the region- are not exclusively dependent on the position of the ITCZ, but also driven by the influence of other mechanisms (e.g. NASH, CLLJ and ENSO), that determine the overall changes in precipitation in Guatemala. This influence of the CLLJ as a modulator of precipitation in the Caribbean side of Guatemala could explain the marked mid-summer drought in the Pacific slope, where the effect of the CLLJ is less evident. The contribution of the CLLJ to the rain shadow effects across the region is difficult to demonstrate given the limitations on available data records as discussed earlier, specifically in mountainous regions of Central America (Karmalkar et al., 2011; Pons et al., 2017). A longer record of hydrological data describing the influence of ENSO and other mechanisms that modulate the precipitation of Guatemala could inform on the interactions between the CLLJ and ENSO and potentially improve our capacity to predict them.

The ENSO phenomenon

The dominant cause of inter-annual variations of precipitation and temperature in Central America is the variability associated to ENSO (Karmalkar & Bradley 2011; Steinhoff et al., 2014). Yet, this mechanism only accounts for around 25% of the inter-annual variability of surface air temperature (SAT) and precipitation, stressing the importance of other climate forces in the region ant their influence on climate (Diaz et al., 2001). However, once an ENSO 3.4 event is onset, the correlation between an ENSO 3.4 index and the principal component of SAT in Mesoamerica is strong (r= 0.8) Karmalkar et al., (2011). This high correlation takes place when there is an active ENSO event, but given its natural non-stationarity and 2-7 year occurrences, the overall attributable contribution on climate anomalies in the region is restricted to the active period when SST anomalies are present. In addition, the expected ENSO events do not necessarily last to the expected length or impacts on the climate of the region (Cid-Serrano et al., 2015).

An inter-basin mode interaction (or *seesaw*), has been identified in the Central American – Caribbean domain as early as 1976 (Hastenrath 1976) and later described in depth by Giannini et al., (2001). This mode corresponds to the influence of ENSO and takes place as a change in the sign of the anomalies of the SLP and SST of the Pacific and Atlantic basins. The ENSO-related precipitation variability at this latitude is dependent on the phase of it and could bring precipitation deficits (under the warm phase) or surplus (under the cold phase) that is, when the eastern Pacific is colder (-SST/+SLP) and tropical Atlantic warmer (+SST/-SLP) then rainfall positive anomalies usually take place in Mesoamerica. The opposite holds as well at least for the Pacific region of Guatemala (Diaz & Markgraf 1992, Giannini et al., 2000; Giannini et al., 2001).

Overall, drier conditions have been associated with ENSO events in the region at least at inter-annual scales (Steinhoff et al., 2015), this is related to the *seesaw* that appears to be active from the boreal summer of onset year of the ENSO event through the mature phase during boreal winter of year (+1) (Giannini et al., 2001). This is particularly relevant to the Pacific coast of Central America because precipitation seasonality and inter-annual variability are strongly related to ENSO and have a direct effect on agriculture and hydropower production (Guevara-Murua et al., 2017).

Although this inter-basin mode might seem simple, the effects of ENSO on tropical climate are generally more complex and extend into the Atlantic Ocean. The teleconnection between ENSO in the eastern Pacific and the Atlantic are currently under research to try to understand the influence of both basins to the tropical climate. For instance, precipitation in the Central American region might be also influenced by SST anomalies in the Atlantic yet, the mechanisms behind the changes in SST in the Atlantic are not fully understood.

To this respect, other two mechanisms may help understand the anomalies in the SST in the Atlantic: the walker circulation and its effect on subsidence over the Atlantic and the change of the meridional SST gradient in relation to the position of the ITCZ (Steinhoff et al., 2015). With respect to the influence of the Atlantic SST anomalies to ENSO, it seems that these can contribute either constructible or destructively to the precipitation of the Central American region depending if the ENSO event is preceded or not by an opposite phase of it (Wu & Kirtman 2010). The relationship between ENSO and the MSD, for instance, remains a current topic of research and past hypothesis relating the MSD entirely to the position of the ITCZ are no longer supported (Magaña et al., 1999). Other processes like the North Atlantic Oscillation (NOA) have not been associated to significantly influence the precipitation variability of Central America and the Caribbean (Hastenrath & Polzin 2013) making the understanding of the mechanisms behind tropical climate a very complicated enterprise (Alexander & Scott 2002).

Limitations of current climate information systems

Overall, climate data in Guatemala is scarce, which limits our understanding of the effect of the several climate mechanisms discussed above over the territory (Hannah et al., 2017; Pons et al., 2017). Aside from the limitations on both instrumental data (Figure 2.1) and terrestrial proxies, there are interactions between several climate mechanisms that are just starting to be studied and understood.

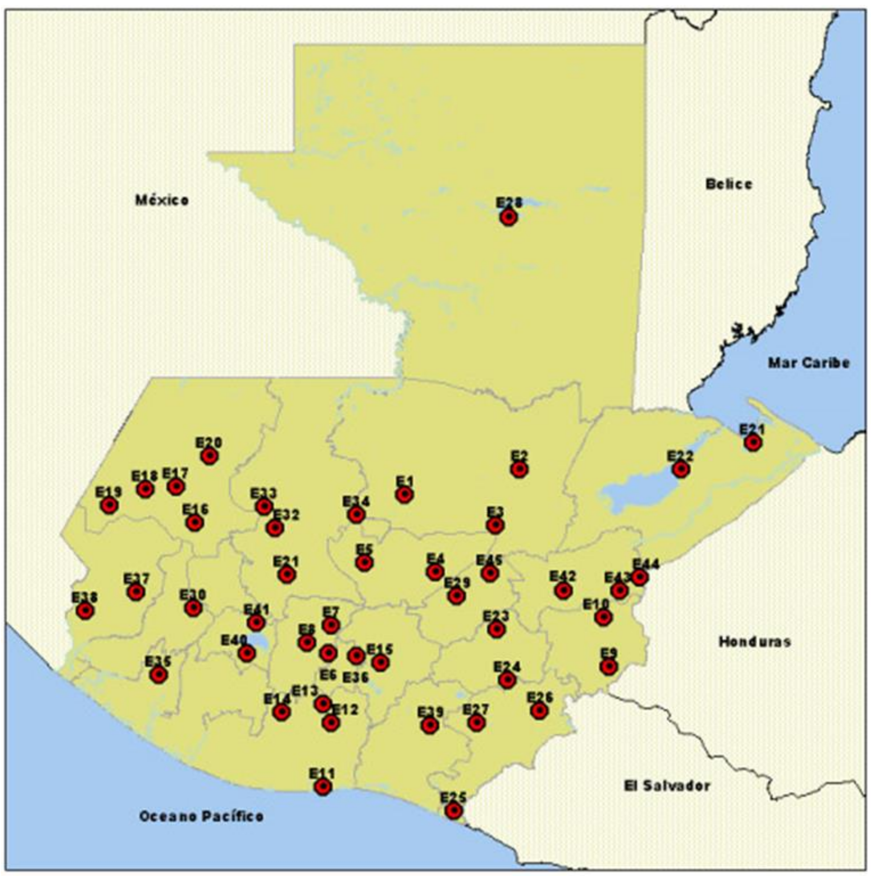

Figure 2.1. Current official weather stations for Guatemala.. Notice the low density of weather stations in the Pacific slope and in the northern lowlands. Source: INSIVUMEH 2017

Despite the importance of precipitation for agriculture and hydropower production in the Central American region, just a few studies have focused on the influence of topography on precipitation (e.g. Waylen & Caviedes 1996; Karmalkar et al., 2011). Yet, these are the type of studies that can deepen our understanding of large scale climate processes and local impacts in the agriculture in Central America.

In terms of the influence of the trade winds on the Central American-Caribbean climate and particularly on precipitation (both convective and orographic), this mechanism remains understudied (Taylor et al., 2011). Similarly, our understanding of the impact of ENSO on regional climate variability in Latin America is incomplete, which is the result of lack of instrumental data and climate proxies, its own natural variability and interactions with other mechanisms that have an influence on the climate in Latin America (e.g. the NASH), highlighting the need for more research on this topic.

In addition, the lack of understanding of the interactions between topography and climate in the region might also limit the use of General Circulation Models (GCM's), regional climate models (RCM's), and gridded data sets (e.g. GPCC v7), especially in mountainous regions (Daly 2006; Imbach et al., 2017). Despite the skills of most general circulation models to reproduce the bimodal regime of precipitation in the region and the overall sign of the precipitation trends in time (Karmalkar et al., 2011; Taylor et al., 2011), the lack of sufficient spatial resolution to account for the differences between sites at a regional and loca scale still limits the opportunities to develop policies on adaptation in the region, especially at the mountainous locations that are ecologically and economically important. In fact, an evaluation of the skills of Coupled Model

Intercomparison Project Phase 5 (CMIP5) model showed large uncertainty in the depiction of mean and standard deviation of precipitation for the Central American region (Hidalgo and Alfaro 2014). Care is usually advised when using these data sets for Central America (Imbach et al., 2017). Although some regional climate models (RCM) for the region like PRECIS (Providing, Regional Climates for Impacts Studies) display a better skill than the GCM's, a dry bias in the wet season and a wet bias in the dry season is produced (Karmalkar et al., 2011), which emphasizes the limitations of these models for policy-making on climate change adaptation of crops and other uses like calculating precipitation for hydropower productivity.

Using dendrochronology to generate climate information

Tropical Paleoclimatology

The tropical region represents several challenges for the study of climate including poor instrumental data and coarse resolution GCM's and RCM's as discussed before. Unfortunately, in-land paleoclimatology studies are also scarce at this latitudes (see Evans et al., 2013). Although the database of high-resolution climate proxies has been expanded since the IPCC assessment report 4 (AR4) (Taylor et al., 2011), climate data remains particularly scarce in this region (IPCC AR 5 2013). Anchukaitis et al., (2013) pointed out that in addition to the low spatial resolution obtained from the models and the low density of weather stations, this topographically complex region adds challenges to the study of climate, particularly on high-elevation regions. Karmalkar et al., (2011) emphasize that some of the GCMs cannot resolve the narrow mountains of the region to be able to capture different climate regimes and climate variability in Central

America. Atmospheric GCMs also fail to reproduce temporal evolution of the annual cycle in precipitation for the same region, especially some local patterns like the bimodal precipitation cycles and mid-summer drought that remain important for several crops in the region (Magaña et al., 1999).

In the absence of long instrumental records and high-resolution GCMs, climate proxies such as tree-ring widths can be used to estimate past precipitation or temperature variability at different timescales (Anchukaitis et al., 2013, IPCC AR5 2013). Moreover, regional-climate patterns (i.e. mid-summer drought) have been addressed by emerging new topics within dendrochronology as part of intra-annual cambium dynamics (Eckstein & Schweingruber 2009). Dendrochronology as a science has evolve for more than 100 years to be the quantitative, rigorous, and well accepted science that it is (Grissino-Mayer et al., 2010), supporting the understanding of global climate by working at finer resolution (both spatial and temporal) than other paleoclimatological proxies.

Tropical dendrochronology

Dendrochronology has much to contribute to the tropical climate research due to the spatial-temporal scales that it can work at (Luckman 2005) alleviating the lack of instrumental data and extending the length of climate records. However, despite an early interest in the tropical region (Brandis 1898; Coster 192; Berlage 1931) the tropics have been largely overlooked by dendrochronologists who believed that indistinct ring anatomy and the fact that seasonal changes tend to be less pronounced in tropical forest than in temperate forest were almost insuperable challenges (Jacoby 1989, Worbes 2002). Luckman (2005) refers to this lack of tree-ring research as the "Tropical Gap". Recently, increasing efforts to refine the methodology have enabled better climate reconstructions at this locations (Martinelli 2003) adding to the overall understanding of global climate. These new tree-ring studies in the tropics (see Tomazello et al., 2009) are particularly important in future syntheses that include paleoclimate models and reconstructions because they can target the last millennium gap (850-1850).

In terms of climate change mitigation, due to the major role of tropical forests in the global carbon cycle, dendrochronology offers potential to better understand forest dynamics and turn-over rates (Rozendaal & Zuidema 2011) broadly unknown in tropical regions (Malhi et al., 2015). Yet, in addition to the technical limitations mentioned before, this region represents a challenge for dendrochronologists, because the phenology, distribution and genetics of the tropical forests have not been studied in depth given the high biodiversity of the region. Deforestation rates also threaten the overall potential for dendrochronology studies due to the difficulty of locating old specimens and the continued degradation of forest near or within protected areas with known dendrochronological potential (De Urioste-Stone et al., 2013; Pons et al.,2017).

Dendrochronology in Central America

According to Briffa (2000) and Worbes (2002), the initial studies on dendrochronology for Central America focused on tree growth periodicity and wood productivity (Hastenrath 1963, Tschinkel 1966, Drew 1998). Worbes (2002) pointed out that in terms of growth-climate relations, the limited use of tropical dendrochronology was related to the convention of temperature as the limiting growing factor, which is nearly constant in the tropics (Rozendaal & Zuidema 2010). On the other hand, precipitation and its role as a primary climatic signal, has been described by Cook &

Kairiukstis (1990) and its positive relation with ring-widths for several tropical species was highlighted by Worbes (1995). However, it has not been often regarded as a growth limiting and periodically occurring factor in the region (Worbes 2002). Anchukaitis et al., 2013 highlighted that the expansion of dendroclimatology into Mesoamerica required the identification an evaluation of species whose rings can be precisely dated and statistically compared with precipitation and temperature variability. This challenge has been successfully addressed in Guatemala by new research (Szejner 2011; Anchukaitis et al., 2013, 2014) leading to robust chronologies for different regions of the country with the use of several species (i.e. *Pinus oocarpa, Abies guatemalensis*). Nevertheless, several regions of the country remain understudied. Anchukaitis et al., (2013) and Stahle (1999) highlighted the potential of conifer species and new sites in mountainous Guatemala to accomplish climate reconstructions for the region.

Regional agriculture and dendrochronology studies

The Central American region has been affected by inter-annual climate variability, specifically by the El Niño-Southern Oscillation (ENSO) phenomenon. According to several authors, there is high confidence that the ENSO will remain the dominant mode of inter-annual variability in the tropical Pacific, with global effects in the 21st century (Christie et al., 2009; IPCC AR5 2013; Steinhoff et al., 2015). Due to the increase in moisture availability, ENSO-related precipitation variability on regional scales will likely intensify. Unfortunately, ENSO variance reconstructions for the last millennium are too uncertain to help constrain the simulated responses of the annual cycle and ENSO (Taylor et al., 2011).

The importance of precipitation and drought patterns to the agricultural systems of the region has been highlighted by several authors (Eaking 2005, Haggar et al., 2013, Laderach et al., 2010, Anchukaitis et al., 2014). Heavy rains caused by hurricanes, for instance, led to great losses from coffee plantations in Guatemala because coffee beans were ready for harvest when the extreme event happened (Tucker et al., 2010). On the other hand, positive ENSO events associated with droughts in the Pacific of Guatemala have had mixed responses on the coffee productivity of this region. For instance the National Coffee Association of Guatemala (ANACAFE) stated that in 2015 that during the 2009/2010 ENSO event, coffee productivity on the western side of the pacific mountains increased up to a 24%, while it decreased 22% in the eastern side.

However, the lack of tree-ring chronologies in Mesoamerica outside of Mexico still restricts the southern extent of precipitation reconstructions hence limiting an in-depth exploration of the trends and effects of these events to agriculture, potable water supplies and hydrological power production (Anchukaitis et al., 2013, 2014).

The understanding of climate variability at a regional scale and in a long-term perspective could be useful for risk management, policy making and overall adaptation strategies crucial for a country heavily dependent on rain fed agriculture (Hidalgo et al., 2016; Donatti et al., 2017; Pons et al., 2017). As discussed before, since the precipitation variability in the Pacific slope of Guatemala is influenced by ENSO at inter-annual scales, local climate proxies sensitive to ENSO variability could be used to characterize the non-stationary behavior of ENSO-related precipitation prior to instrumental records in Guatemala. Moreover, tropical climate reconstructions should be based on proxies of tropical origin (Worbes 2002) which facilitates the local interpretation of the effects of such mechanisms on agriculture. Some of the climate proxies that have proven to capture some sensitive from ENSO in Guatemala include tree-ring widths of the Guatemalan Fir (*Abies guatemalensis*) (Anchukaitis et al., 2013, 2014). The use of dendrochronological proxy records of climate from coniferous species in tropical North America, and specifically those of high peaks of Central America have been proposed as good candidates to reconstruct climate due to a pronounce seasonality (Arno and Hammerly 1984; Perry 1991).

The information generated by dendrochronology could be used to inform stakeholders and decision makers on the precipitation variability and trends and the impact of these on agriculture at a regional and local scale. Not only could this help place the current precipitation trends in long-term context but also it could help validation processes of the proposed climate models for the region (Karmalkar & Bradley 2011; IPCC AR5 2013; Steinhoff et al., 2014). Nevertheless, the advancement of tropical dendrochronology imposes several well-known challenges (Schulman 1994). Aside from locating old trees forming annual rings sensitive to climate, the little knowledge on the ecophysiology of tree species (e.g. dormancy periods) and limited instrumental records used to calibrate and validate the climate reconstructions requires further examination (Anchukaitis et al., 2013; Pons et al., 2017).

CHAPTER THREE
THE CLIMATE SENSITIVITIES OF COFFEE PLANTS

Having discussed the main mechanisms behind the climate in Central America and the current limitations regarding our understanding of those mechanisms, it becomes relevant to illustrate how precipitation and temperature controlled by those mechanisms affect coffee plantations. Coffee plants are very sensitive to climate changes and extreme weather events because precipitation and temperature changes have a direct influence on coffee phenology (Fournier y Di Stéfano 2004; DaMatta & Ramalho 2006; Bunn et al., 2014, Rahn et al., 2014; Ovalle-Rivera et al., 2015). Differences in precipitation and temperature can trigger early or late flower blooms or completely halt flowering during extended droughts (Camargo1985; Villers et al., 2009). Aside from the physical damage from precipitation extremes and changes in rainfall timing, the associated changes on flower blooming have a direct impact on the producing costs. Because of thesefactors, rainfall has been recognized as the most restrictive climate feature in coffee growing regions including its total annual and monthly distributions (Descroix and Snoeck 2004).This argument has been supported by the National Coffee Association of Guatemala (ANACAFE) in a recent symposium (ANACAFE 2017), where the variability of precipitation was acknowledge as a critical factor of Guatemala's coffee sector. The perception of coffee farmers is that the timing and amount of precipitation seems to be changing. A recent study by Ridley (2011) illustrates both the suitable and optimal mean annual temperatures and suitable and optimal total annual precipitation for *Coffea arabica* from several authors. The results are summarized in the following table (Table 3.1).

Table 3.1 Suitable and optimal mean annual temperatures and suitable and optimal total annual precipitation for *Coffea Arabica.*Modified from Ridley 2011.

	Temperature Range in °C	**Precipitation Range in mm**
Suitable	15-30	800-2,500
Optimal	18-22	1,200-1800

Coffee is very sensitive to climate variations. For instance, subtle temperature increases moving away from the optimal temperature of 18-22°C (Ridley 2011) can lead to loss of quality due to an accelerated ripening of the beans (Alègre, 1959; Camargo, 1985). This narrow optimal also changes with the phenological stage of the plant (DaMatta & Ramalho 2006). Humidity, usually rain-fed, is difficult to manage because each different phase of the coffee cycle (see Camargo and Camargo 2001) is associated with specific water requirements (Carr 2011). Coffee farmers have traditionally managed this delicate equilibrium between temperature and precipitation requirements by making use of shade systems to regulate microclimate. Pruning the shade trees allows them to manage the solar radiation input and the relative humidity within the coffee plots. Recently, other mechanisms like allowing pastures to grow in-between coffee plants have been used to try to retain soil moisture. Although these mechanisms remain the main tool for farmers to buffer climate variability, their functionality is determined by a marked rainy season that allows to calculate the right time for pruning the shade trees and allowing the pastures to grow. Climate projections suggest this marked seasonality could be changing (Baca et al., 2014).

Effects of weather extremes and climate variability on Guatemalan coffee productivity (*Coffea arabica*)

Major challenges for coffee producers in Guatemala include price instability, climate change, and incidence of pests (Castellanos et al., 2013). The volatility of market prices over the last several decades led to the abandonment of many coffee plantations by smallholder producers and land use changes in medium to large producers. Furthermore, while low prices continue to devastate rural economies and threaten the ecosystem services associated with traditional coffee production, new challenges related to climate variability further threaten the sector (CEPAL 2002; Eaking et al.,2005; Castellanos et al.,2013; Holland et al., 2016). After the early 2000's market-related coffee crisis, exacerbated by droughts in the same years, permanent employment in Central America's coffee segment fell by 50% and seasonal employment by 21%. It is not only droughts that affect coffee; heavy rains have often led to great losses (IADB 2002; Bacon 2005; Eaking et al., 2005; Tucker et al., 2010; Castellanos et al., 2010). In 2006, 53% of coffee farmers reported coffee crop losses; half of which described the cause to be excessive rainfall in Guatemala while the other half cited a lack of rain (Castellanos et al., 2010). This not only highlights the impact of precipitation extremes in different parts of the country but also the lack of monitoring and forecasting systems in place. However, limited climate data restricts our capacity to analyze the historical relations between agriculture and climate in Guatemala.

In terms of pests and infestations, coffee leaf rust, a fungus affecting coffee plantations, generated the most recent crisis in the coffee sector and has been related to changing climatic conditions (Georgiou et al., 2014). The magnitude of this crisis led to crop losses up to 30% for the 2012/13 harvest. Coffee leaf rust has been related to an increase of minimum temperatures in the mountainous regions of the country (Camargo1985; Villers et al., 2009; Georgiou et al., 2014; Avelino et al., 2015; Pepin et al., 2015). Unfortunately, coffee leaf rust continues to be a main source of concern for coffee farmers in the region (Holland et al., 2016) as it continues to infect coffee plants in 2017 as shown by the figure 3.1.

Figure 3.1. Coffee plant (*Coffea arabica*) infected with coffee leaf rust (*Hemileia vastatrix*). (a) The rust preferably attacks the old leaves causing defoliation. (b) The rust penetrates the leaf from underneath going into the plant´s stomata. (c)The damage causes an initial chlorosis followed by a necrosis. Source: Diego Pons 2017.

Climate projections and their potential impact on Guatemalan Coffee

Historical, present and projected climate data at a regional and local scale for Guatemala are scarce (Pons et al., 2017). This limits our understanding of the impact of underlying climate mechanisms in the region and imposes limitations to climate modelers and adequate adaptation strategies (Hannah et al., 2017). While in the last 15 years a trend towards an increment in precipitation unevenly distributed in the country has been reported by the national meteorological institute (INSIVUMEH 2016), several long-term climate projections for Guatemala predict a reduction of precipitation in both dry and wet seasons (Neelin et al., 2006; Magrin et al., 2007; UNFCCC 2007; Läderach et al., 2010; Karmalkar & Bradley 2011; Baca et al., 2014; Ovalle-Rivera et al., 2015). This projected decrease in long-term precipitation could significantly impact the coffee industry in some parts of the country like the eastern highlands near the dry corridor which is currently under the precipitation optimal and benefit other regions with a surplus of rainfall over the optimal parameters described before. Aside from the climatological influence of precipitation changes over the biology of coffee plants, other segments of the coffee production chain could be heavily impacted. For instance, potential changes in rainfall patterns are likely to lead to severe water shortages and/or flooding which could affect production of wet-processed high-quality *arabica* coffees planted in Guatemala. In this type of production of wet-processed coffee, the beans are removed from the fruit with water and then allowing fermentation (with water again) to remove a mucilage layer, washed, and dried (Figure 3.2). This wet-processed coffee produced in Guatemala generally scores higher than the dry-processed one, resulting in a better price for the coffee producer (UNFCCC 2007; Noah 2009; Fisher & Victor 2014).

Figure 3.2. Coffee being washed by workers from a farm within the Samalá River watershed. Source: Jessica Hook 2015

Figure 3.3. Fermentation tank used in the *lavado* processing of coffee. Source: Jessica Hook 2015

Severe water shortages as a result of changing rainfall patterns and trends could potentially not only reduce coffee productivity due to water stress but it could also limit producer's abilities to carry out this type of wet-processed coffee production (Figure 3.3). On the other hand, in a scenario with increased precipitation or flooding events in coffee growing regions, the result could be equally harmful due to pouring rain dropping the coffee beans when they are ready to harvest or flooding events directly destroying the crops which could led to great losses as it has in the past (IADB 2002; Bacon 2005; Eaking et al., 2005; Tucker et al., 2010; Castellanos et al., 2010).

The combination of increasing temperatures and increased precipitation variability has led to a projected 53% loss of area suitable for coffee in Guatemala by 2050 (CIAT 2012; Baca et al., 2014; Ovalle-Rivera et al., 2015). Two main hotspots are expected to show the biggest loss in the suitable areas for growing coffee; the eastern region near the border with Honduras and the entire Pacific slope (Figure 3.4).

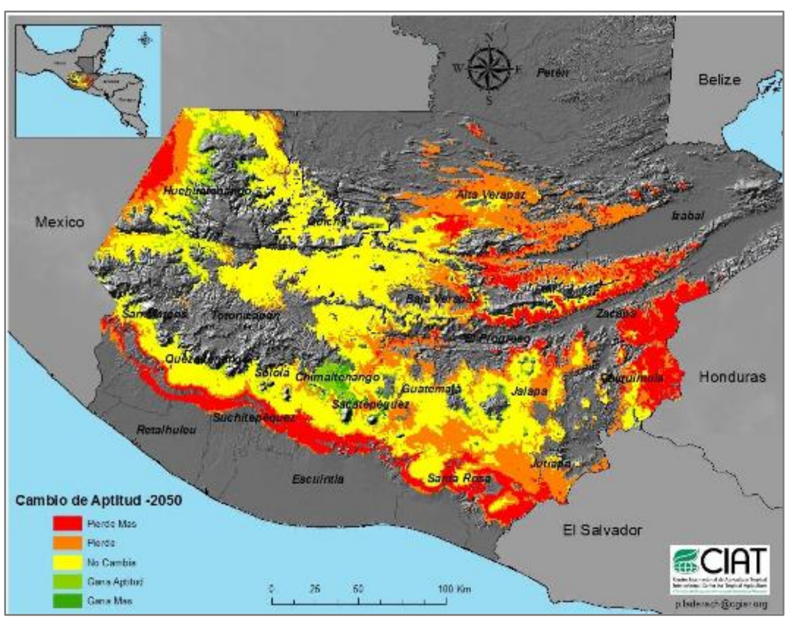

Figure 3.4: The map shows the suitability loss (red) for area planted with coffee towards 2050.A total 53% of the area currently suitable for coffee could be lost. Source: CIAT 2012.

CHAPTER FOUR

PRECIPITATION RECONSTRUCTION IN THE PACIFIC MOUNTAINS OF GUATEMALA

"*The farther backward you can look, the farther forward you are likely to see*."

\- Winston Churchill

Introduction

In Guatemala, the timing and quantity of rainfall is critical to sustain cash crops and subsistence agriculture (Pons et al., 2017). This is particularly true for the southern slope of Guatemala´s volcanic range where historical suitable agro-ecological conditions that include marked rain seasonality and volcanic soils have made the Pacific slope of Guatemala an optimal location for agriculture (Finegan and Bouroncle 2008). Yet, historical and projected climate data at a regional and local scale for Guatemala are scarce (Pons et al., 2017). This limits our understanding of the impact of underlying climate mechanisms in the region and imposes limitations to climate modelers and adequate adaptation strategies at a local level (Hannah et al., 2017).

The variability in annual precipitation influenced by the ENSO ocean-atmosphere mechanism has been described as the key factor that accounts for inter-annual hydrologic deviations in the region (Steinhoff et al., 2014; Hidalgo et al., 2016). These precipitation anomalies in the Pacific slope of Guatemala translate into droughts, increased precipitation, and floods that have large impacts on a vast number of crops in the region with the highest impacts on coffee (Soto et al., 2015; Imbach et al., 2017). These variations in precipitation are however, poorly recorded by a limited network of weather stations and a lack of terrestrial climate proxies (e.g. dendrochronology) which in turn limits our understanding of low-frequency events and historical extremes at low latitudes (Evans et al., 2013; Hannah et al., 2017).

The understanding of climate variability at a regional scale for risk management, policy making and adaptation strategies is crucial for a country so dependent on rain fed agriculture (Donatti et al., 2017; Hidalgo et al., 2016; Pons et al., 2017). The lack of scientific and technical information deters policy makers from developing policies to help smallholder farmers adapt to climate change (Donatti et al., 2017). Climate proxies potentially sensitive to ENSO variability can be used to characterize the non-stationary behavior of ENSO prior to instrumental records in a region heavily influenced by this mechanism as it is expected to remain the dominant cause of inter-annual variability for the region throughout the 21st century (Christie et al., 2009; IPCC AR5 2013;Steinhoff et al .,2014).

Dendroclimatological research in the tropics is an increasingly studied topic (Wils et al., 2011), with some studies associated to the ENSO teleconnections to tropical tree growth (Enquist & Leffer 2001; Trouet et al., 2010, Anchukaitis et al., 2014). Tree-ring growth research has been studied in Central America as early as 1960´s (Hastenrath 1963; Tschinkel 1966) and more recently (Stahle et al., 2012; Szejner 2011; Anchukaitis et al., 2013, 2014). The use of dendrochronological proxy records of climate from coniferous species in tropical North America, and specifically those of high peaks of

Central America have been proposed as good candidates to reconstruct climate due to a pronounce seasonality (Arno and Hammerly 1984; Perry 1991).

The information generated by dendrochronology could be used to inform stakeholders and decision makers on the precipitation variability and trends and the impact of these on agriculture at a regional and local scale. Not only could this help place the current precipitation trends in long-term context but also it could help validation processes of the proposed climate models for the region (Karmalkar & Bradley 2011; IPCC AR5 2013; Steinhoff et al., 2014). Nevertheless, the advancement of tropical dendrochronology imposes several well-known challenges (Schulman 1994; Pons et al., 2017). Aside from locating old trees forming annual rings sensitive to climate, the little knowledge on the ecophysiology of tree species (e.g. dormancy periods) and limited instrumental records used to calibrate and validate the climate reconstructions requires further examination (Anchukaitis et al., 2013; Pons et al., 2017). Although critical for calibration processes, assessing the availability of instrumental climate records to calibrate dendrochronology proxies is not usually addressed in tropical dendrochronology guidelines (Stahle 1999; Worbes 2002). Because of the lack of instrumental data in Guatemala (Pons et al., 2017), the outcomes of using alternative climate data sets used to calibrate climate proxies is implicitly addressed in this study.

The aims of this study are: 1) to demonstrate successful cross-dating and climate sensitivity of *Abies guatemalensis* in the Pacific southern slope of Guatemala, 2) to evaluate the climate signal against local instrumental and regionally gridded climate data, 3) to discuss the implications of using different sets of data to calibrate tree-ring width series in a tropical setting, and 4) to evaluate the potential of *A. guatemalensis* proxy records to extend precipitation records for the Pacific slope of Guatemala. This information could then be used to incorporate knowledge of inter-annual and decadal variability in risk management strategies, place recent trends in a long term perspective and help predict precipitation patterns, especially those related to ENSO.

Methods

Study site

Figure 4.1 Study location in southern Guatemala. The Samalá River Watershed is highlighted. Sampling location is indicated by a green star and coffee growing areas are emphasized in gray. Source: Pons et al., 2017.

The Guatemalan fir (*A. guatemanlensis*) has demonstrated reliable cross-dating, sensitivity to climate (Anchukaitis et al., 2013) and has been successfully used to reconstruct precipitation in the western highlands of Guatemala (Anchukaitis et al., 2014). Based on this success, I evaluated the potential of *A. guatemalensis* as a climate proxy in the Pacific basin of Guatemala (Stahle 199). I assessed the dendrochronological potential of the species to reconstruct climate in southern Guatemala near Quetzaltenango, Guatemala's second biggest city. The forest stand used here had been previously identified by Andersen et al., (2006) as one of the remaining *A. guatemalensis* forests of the department. The forest, which became a protected area in 1995, is well-known to the communities of Zunil who co-manage it for both conservation and timber harvesting (De Urioste-Stone et al., 2013). The name of the forest in local K´iché language is Kanchej. It is located in the upper Samalá River watershed which covers 1,500 km² across the departments of Quetzaltenango, Retalhuleu and Suchitepéquez (Figure 4.1). Located between Santiaguito and Santo Tomas volcanoes, it follows the Zunil Fault Zone to the south (Bennati et al., 2011).

Geologically, the area encompasses igneous and metamorphic rocks in the upper watershed and quaternary alluviums on the coastal plain. The average annual precipitation within the watershed ranges from 2,000 mm at high elevations and along the coast, to 5,500 mm near the middle altitudes of 630 m.a.sl.. The average annual temperature ranges from 10ºC at the highest elevation to 25.5ºC on the coastal planes (MAGA 2002). The *A. guatemalensis* trees used here as a climate proxy are distributed across the high mountain range in Quetzaltenango and Sololá departments from 2,700 to 3,600 m.a.s.l.. This complex topography creates an altitudinal variation that gives room to a wide assortment of microclimates allowing for diverse agricultural products, of which coffee is the most important (Imbach et al., 2017).

Tree-ring Data

I collected two to three increment core samples from 60 trees at the Kanchej forest near Quetzaltenango located at 14°46'39.68"N, 91°26'17.94"W at 3,300 m.a.s.l.. A first set of samples was collected in the boreal summer of 2014 and a second one in the boreal summer of 2015. Samples were dried, mounted, and sanded. Skeleton plots were created from each sample following the cross-dating procedure described by Stokes & Smiley (1968), which allows for visual cross-dating and an initial dating for the samples. Some samples were excluded because highly growth-suppressed sections prevented measurements of ring widths (Stahle et al., 2011). A first assessment of the dendrochronological samples reveled advanced early wood development by July of the current growing year with no signs of late wood formation at the time of sample collection in the two field visits in July (Figure 4.2).

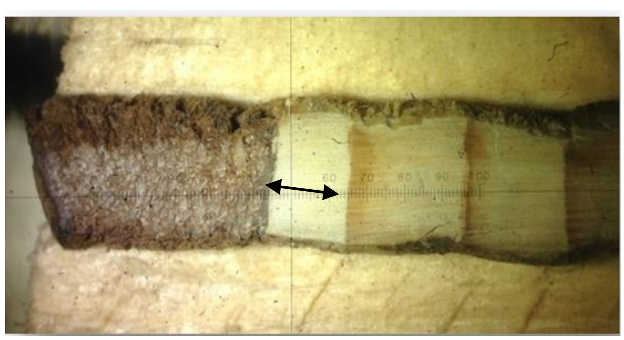

Figure 4.2. Early wood formation of *Abies guatemalensis* during the month of July of 2015.

The samples were measured to 0.001mm precision using a Velmex measuring table and the MJ2X software. The samples were then cross-dated and verified for adequate statistical correlations among samples and climate sensitivity using COFECHA (Holmes, 1983). After the cross-dating, I used the program ARSTAN (Cook 1985) to standardize and detrend the ring-width series using a 50 year smoothing spline to 50% amplitude of the individual series length. This de-trending function was tested for each of the samples during an interactive process to verify the adequate removal of non-climatic factors in the tree series. The AR-standardized chronology (Cook 1985), which has proven useful in past climate reconstructions using *A.guatemalensis* in the country, was used in this study in order to preserve potential autoregressive structure related to climate variability (Anchukaitis et al., 2014). However, the residual chronology was also used for the climate sensitivity assessment to analyze the influence of a reduced autocorrelation series.

Climate Data

The instrumental data used in this study is a composite of two weather stations in the region. The precipitation data was derived from the Labor Ovalle weather station which is owned and managed by the National Weather Institute of Guatemala (INSIVUMEH), and it is located in Quetzaltenango at 14° 52.227'N, 91° 30.858'W, 12.8 km northwest of the forest stand of Kanchej (14° 46.693'N, 91° 26.192'W) at an altitude of 2,388 m.a.s.l. The precipitation record from this station begins in 1980 which was the longest, more robust record available. The temperature data was collected from the Zunil weather station located at 7.8 kilometers from the reconstruction site at 14° 45.433'N, 91° 30.067'W at an altitude of 1,880 m.a.s.l. starting in 1982. This represented 9 more years of temperature records than those available from Labor Ovalle weather station.

The precipitation dataset has no missing values. The temperature dataset from Zunil however presented a few missing values (11%) in the record that were filled using the approach suggested by Pappas et al., (2014) which suggest using an averaged value between the previous and following records.

In order to evaluate the potential differences between using local instrumental and gridded climate records to assess the climate sensitivities of the reconstructions, a longer (1901-2013) record of gridded monthly precipitation data from the Global Precipitation Climatology Centre gridded precipitation data (GPCC version 7, Schneider et al., 2015), and mean temperatures from the high-resolution Climate Research Unit data set (CRU TS 3.34.01) were also used to evaluate the climate sensitivity of the chronology and to assess the differences between the different these data sets and the climate sensitivity for *Abies guatemalensis* in this location. The mean distribution of the monthly precipitation and temperature records from the instrumental data for the period 1982-2014 is presented in figure 4.3.

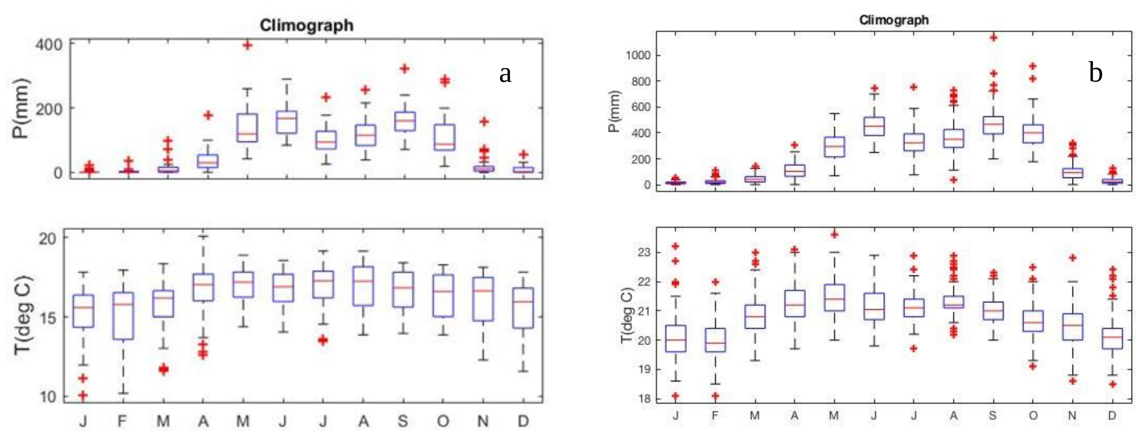

Figure 4.3. (a) Distribution analysis of climatological records from instrumental data from Labor Ovalle (precipitation) and Zunil weather station (temperature) for the period 1980-2013 and 1982-2013 and (b) gridded precipitation from GPCC version 7, period 1903-2013. Source: INSIVUMEH 2017, INDE 2017, and Schneider et al. 2015.

The distribution of the monthly precipitation and temperature records from the gridded data were truncated for the period 1983-2013 at 0.5° and 1.0° for comparison purposes and are presented in figure 4.4. The period (1983-2013) is similar to the one covered by the Labor Ovalle weather station near the reconstruction site. The different results from using alternative time-periods is assessed in future sections.

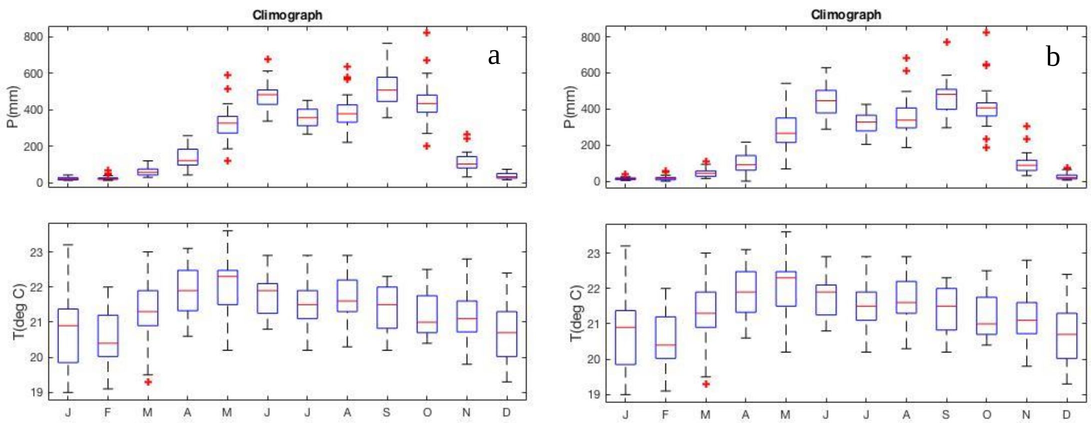

Figure 4.4. (a) Distribution analysis of climatological records from gridded precipitation from GPCC version 7, period 1983-2013 at 0.5° and (b) 1.0° spatial resolutions (Schneider et al., 2015).

Climate Sensitivity Assessment

The chronology was evaluated for climate sensitivity against monthly values of precipitation and mean temperature from the instrumental records described above. The precipitation records were obtained from the Labor Ovalle weather station located in Quetzaltenango. The temperature records where obtained from Zunil weather station as mentioned before.

As a first approach to explore individual monthly correlations for precipitation reconstruction, I performed a simple Pearson correlation analysis using the *dcc* function from the Treeclim package (Zang & Biondi, 2015). The instrumental data used to evaluate precipitation sensitivity was that from Labor Ovalle weather station described above because it was the longest precipitation record available near the tree-ring sampling site (Huante et al., 1991). Limited by the span of the instrumental data used in this study (n =34 years), evolutionary and moving intervals were not used to test for temporal changes between the tree-ring data and the climatic relationships for the instrumental data. In order to evaluate a potential lag climate effect on the tree-ring width time series, I analyzed the climate sensitivity of the *A. guatemalensis* standard chronology (Cook 1985) using a 16-month window starting in June of the previous year and finishing in September of the current growing season. The use of a window of 12 or more months is usually recommended when evaluating climate sensitivity (Meko et al., 2011) because radial growth could be associated with previous year climate (Fritts 1976). The decision was also supported by the little knowledge on the ecophysiology of the species (Anchukaitis et al., 2013) and the degree of growth of early wood during the two visits to the field in July 2014 and 2015 as described in tree-ring data section.

After this first evaluation, I used the *seascorr* function (Meko et al., 2011) in MATLAB to assess potential seasonal correlations (signal integrated over months) using exact simulation of the tree-ring series (Percival and Constantine 2006). The analysis was performed against the instrumental data from the Labor Ovalle (precipitation) and Zunil (temperature) weather stations (1982-2014) against a similar period (1984-2013) for GPCC v7 gridded precipitation at 1.0° spatial resolution and CRU TS 3.34.01 temperature estimates for 1, 2, 3 and 4 month composites. To test for any potential differences in climate sensitivity of the chronology using a longer gridded period, a subsequent seasonal correlation analysis was performed for the entire gridded climate record (1903-2013) for both precipitation and temperature. The 0.5° and 1.0° spatial resolution data from the GPCC precipitation gridded data were also compared to a time period similar to that of the instrumental data to evaluate potential differences in climate sensitivity that might be dependent on the spatial resolution of the datasets. In all the cases precipitation was evaluated for simple correlations as the limiting climate factor and temperature was used to analyze partial correlations. This decision was based on the notion that growth of conifers in tropical regions is mostly influenced by precipitation (Fritts 2000: Villanueva-Díaz et al., 2007).

Periodicity analysis and precipitation-ENSO teleconnection

The first approach used to evaluate potential associations between the tree-ring width and ENSO was to perform a spectral analysis using *seascorr* function from MATLAB (Meko et al., 2011) which allows for a better understanding of the periodicity of the variability in the chronology which can then be comparted to know ENSO periodicities. Therefore, I conducted a spectral analysis on the *A. guatemalensis* chronology to evaluate the properties of the variability of the time series. The analysis was performed to a 107-year span associated to the mean segment length for the subset of samples from our chronology (where expressed population signal remains higher than 0.85). After this, the *A. guatemalensis* chronology was compared to a seasonal (June-July-August) and monthly ONI indices (ENSO 3.4 SST) for the period 1950-2013 to explore potential relationships.

Reconstruction methods

In locations where tree growth might be limited by a single climatic factor (e.g. precipitation) a linear regression can be successfully used to reconstruct climate (Biondi 1997). In this study I selected ordinary least squares (OLS) as a linear regression model to reconstruct climate. I used the *skills* function of the Treeclim package in the R program to determine the reconstruction skills using split-calibration (Michaelson 1987). I used 50% of the available years (1982-2014) for calibration and the rest for verification purposes (Zang & Biondi 2015). In this type of analysis, a general exploration between climate variables and growth is assessed followed by the selection of the strongest variables used later for reconstruction purposes (Zang and Biondi 2015). Three validation statistics were calculated to assess the skills of the reconstruction; the root mean squared error (RMSE) the reduction of error (RE), and correlation coefficients (Cook et al., 1994; Fritts et al., 1990).

Results and Discussion

Cross-dating and anatomical features

The anatomic characteristics of *Abies guatemalensis* in this region are similar to those reported by Anchukaitis et al., (2013). Some samples showed local absent rings and cellular trauma (Figure 4.5). Several growth-suppressed sections, usually present in the last 30 years, prevented further ring counting in most of the samples from the northwest aspect of the mountain. This growth suppression has been recently reported for the same species in other regions of Guatemala (Anchukaitis et al., 2013).

The reported interseries correlation and mean sensitivity of our chronology are 0.447 and 0.273 respectively (Fritts, 1976; Holmes, 1983), which allows for the carrying out of climate analysis and reconstructions (Anchukaitis et al., 2013). The mean segment length for this subset of samples is 107 years, which could be extended in the future with more sampling (see Appendix B for time coverage by individual tree sample length).

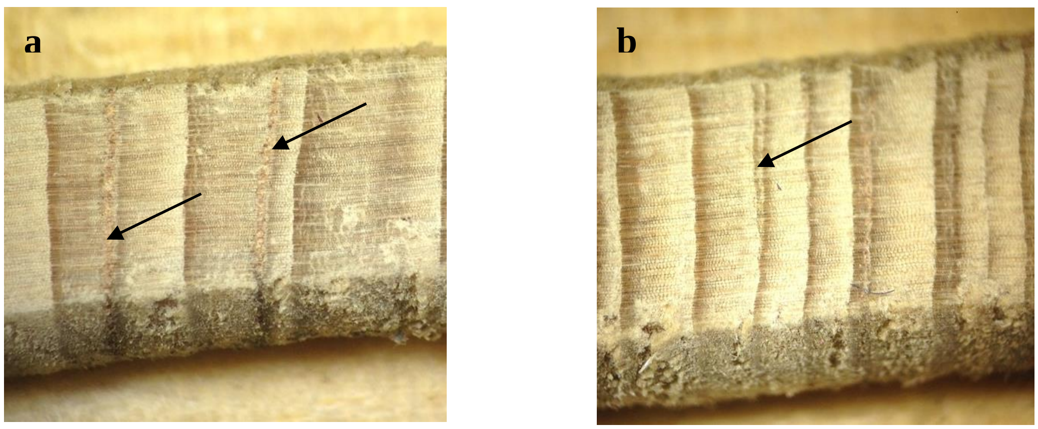

Figure 4.5. (a) Cellular trauma and (b) locally absent ring on samples of *Abies guatemalensis*.

To determine the level of coherence of the *A.guatemalensis* chronology, the expressed population signal was calculated using a 50-year moving window and a 25-year overlap (Grissino-Mayer 2001). The strength of common patterns of tree growth was used to determine the robustness of the reconstruction and the total years used in the final reconstruction were determined by an EPS value higher than 0.60. This is greater than 0.85 back to 1920, remains higher than 0.63 towards 1900 and finally goes down to 0.6 before 1880 probably due to sample depth (Figure 4.6). The *A. guatemalensis* samples collected in July 2014 came from trees located on the north-west aspect of the mountain in the Kanchej forest.

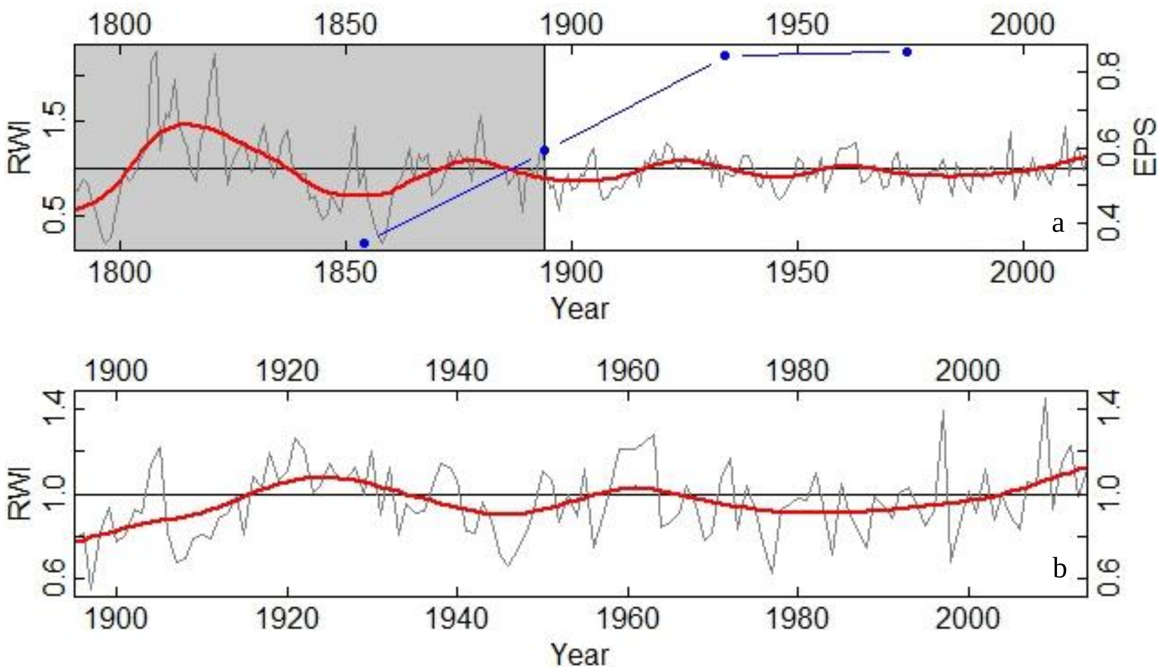

Figure 4.6. (a) Standard chronology from *Abies guatemalensis* showing the EPS cut at 1889 and (b) final standard chronology.

These samples had less clear ring boundaries and were overall more difficult to cross-date when compared to the samples collected in July 2015.). Northern aspects of Guatemalan mountains are usually wetter and cooler and this could explain the poor drought sensitivity of the first samples taken in the northern aspect (Pons et al., 2017). This pattern started to change on a second visit to the field in July of 2015 where more samples were collected moving southwest from the original sampling site. The first sampling site also corresponded to the boundary of the forest and annual agriculture. The samples collected in July 2015 corresponded to a transect going down the hill from the initial (2014) sampling site and towards the south-west aspect of the same forest stand. Overall, clearer ring boundaries were identified, increased interseries correlation was obtained and better climate sensitivity was achieved as discussed in the next section.

Climate sensitivity assessment

The correlation analysis performed between monthly precipitation and temperature values from the Labor Ovalle and Zunil weather stations against the AR-standard chronology using Treeclim (Zang & Biondi 2015) are shown in figure 4.7 where the significant (0.05) monthly correlations are presented in continuous lines. In terms of the climate sensitivity of the chronology to precipitation using individual monthly values from the instrumental records available, the results from Treeclim show a positive correlation to the June, July, and August from previous year. Also, inverse correlations were found with November and December from previous year as independent months. The analysis using Treeclim also suggests a relatively high negative correlation with temperature from the month of January of the current year, which is muted when running the *seascorr* (seasonal correlation) analysis as discussed in further sections.

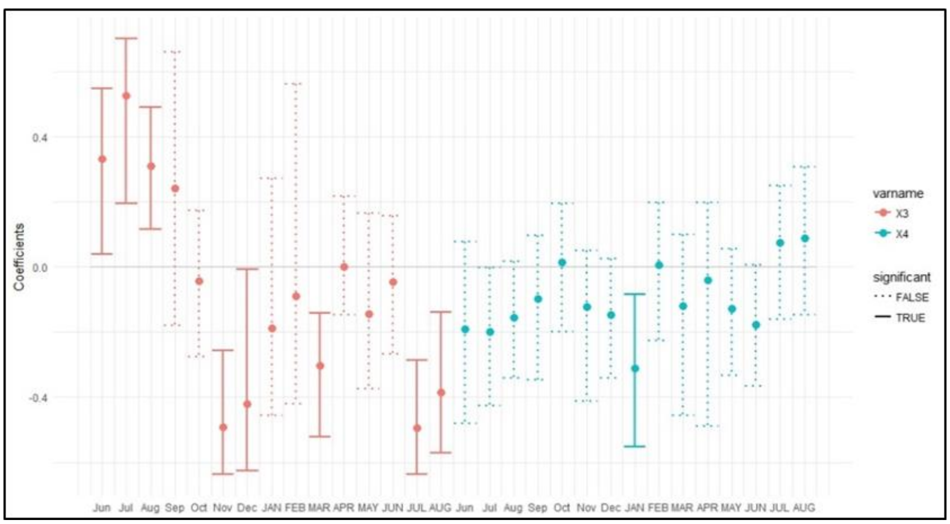

Figure 4.7. Climate sensitivity analysis of proxy-climate using the correlation function analysis from Treeclim (Zang & Biondi 2015). Precipitation correlations are shown in red and temperature in blue. Capitalized months represent current growing year.

After this first assessment of climate sensitivity for independent monthly correlations, the *seascorr* function of MATLAB (Meko et al., 2011) was used to evaluate seasonal composites against the standard chronology. The results from *seascorr* (seasonal analysis of 1, 2, 3, and 4 months) using instrumental data from the Labor Ovalle (mean precipitation) and Zunil (mean temperature) weather stations are similar to the individual monthly assessment performed by Treeclim as shown in figure 4.8. However, when using the gridded data (GPCC data at a 1.0° and CRU TS 3.34.01) for the 1982-2013 period, some of that sensitivity for the monthly composites was lost (Figure 4.9). When the same analysis was performed against the gridded data for the 1903-2013 period, the correlations changed as seen in figure 4.10. Although June and July remain significant in the 4-month composite, the long-period climate sensitivity analysis using the gridded data suggests a significant correlation with the March-April-May composite that was not present in the previous, short-period analysis (Figures 4.8 and 4.9).

A different seasonal correlation analysis was performed using the residual chronology against the same instrumental data and gridded precipitation data GPCC data at a 1.0° and 0.5° at to assess for changes in the climate sensitivity due to the spatial resolution of the gridded data sets against the instrumental records. The results of this seasonal correlation analysis (see Appendix B), suggest that the finer resolution precipitation GPCC data (0.5°) preserves similar climate sensitivity correlations in respect to both the instrumental and the gridded GPCC data at 1.0° for this region. Although the correlations are somehow diminished, the months of climate influence remain consistent among these data sets.

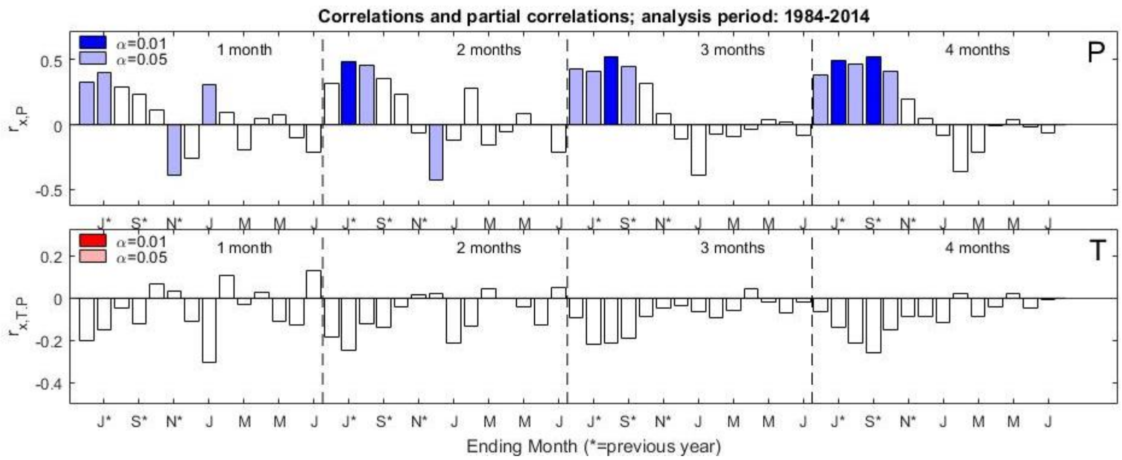

Figure 4.8. Monthly and seasonal correlations of tree-ring series against instrumental data for the period 1984-2014 using data from Labor Ovalle (precipitation) and Zunil weather station (temperature).

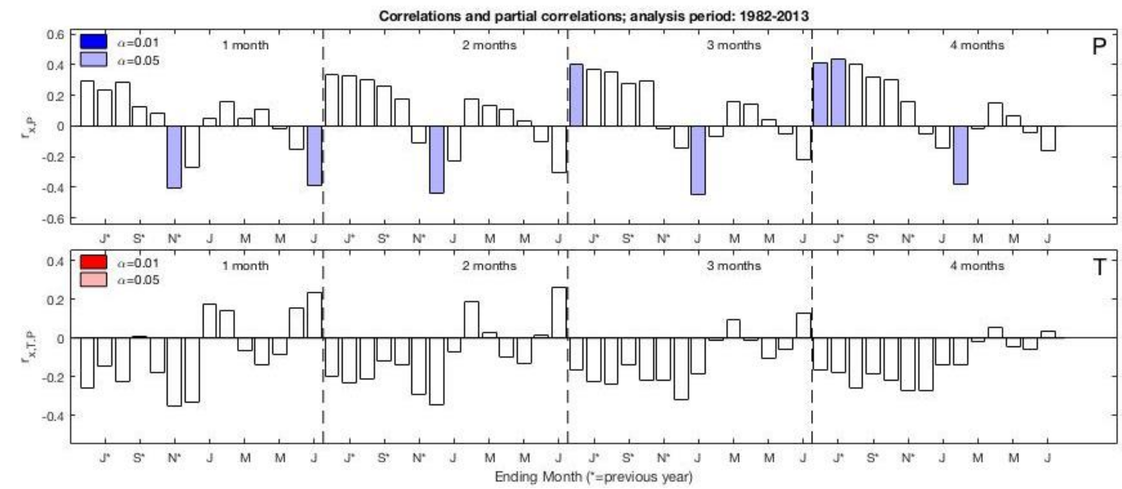

Figure 4.9. Monthly and seasonal correlations of tree-ring series against gridded GPCC v7 at 1.0° and CRU TS 3.34.01 data for the period 1982-2013

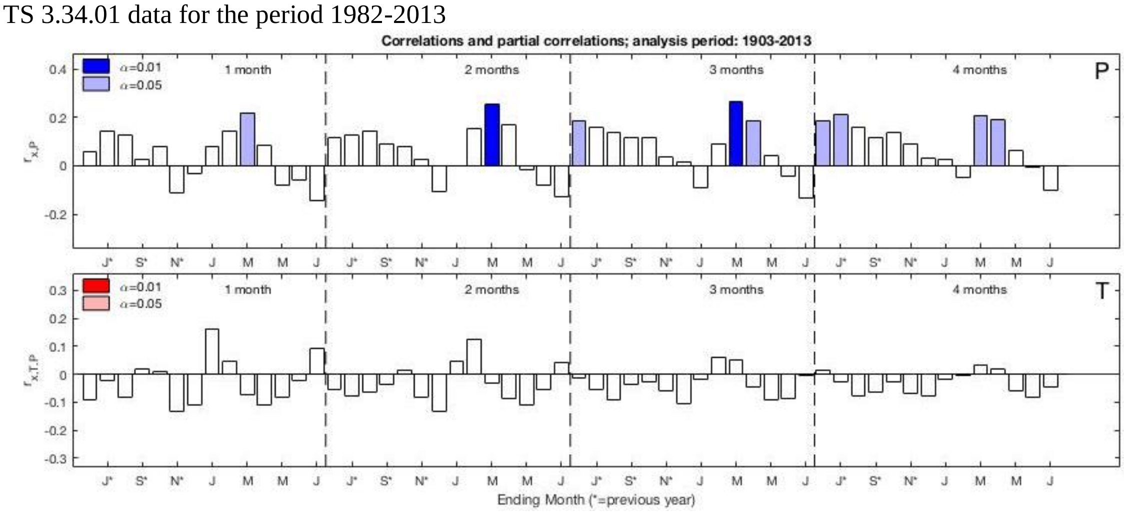

Figure 4.10 Monthly and seasonal correlations of tree-ring series against gridded GPCC v7 at 1.0°and CRU TS 3.34.01 data for the period 1903-2013.

The results from *seascorr* using instrumental data for the 30-year period of available information suggest a positive significant correlation to previous June and July precipitation for the 1-month composite, previous July-August mean precipitation in the 2-month composite, previous June-Sept mean precipitation for the 3-month composite and previous June-October mean precipitation for the 4-month composite. Overall, the climate sensitivity analysis using gridded data at both different timescales (1982-2013, 1903-2013) and resolutions (1.0° and 0.5°) consistently suggests a previous June-July significant correlations.

A similar association has been reported for *Abies lasiocarpa* in Washington and Oregon, U.S.A. (Peterson et al., 2002). In the study from Peterson et al., (2002), previous boreal summer precipitation from July-August showed a significant correlation at 0.05 and also significant negative correlations in the growing year for December-March (r = -0.27, $p < 0.05$), which is similar to the November-December negative correlations described in our study (Figure 4.8 and 4.9).

Negative correlations with previous year precipitation have also been reported in other studies for *Pinus pseudostrobus* and *Pinus devoniana* in central Mexico (Magre et al., 2015), with *Juniperus virginiana* in the United States (Maxwell et al., 2012) and with *Quercus robur* in Slovenia (Hafner et al., 2015). In China, *Abies fargessi* has been evaluated for climate sensitivity finding significant negative correlations to previous November precipitation (Dan et al., 2007). In a different study in Mexico, *Abies religiosa* showed significant positive correlations to previous October precipitation (r = 0.44, $p < 0.05$) and an insignificant negative correlation with December similar to the one reported in this study (Huante et al., 1991). However, they reported a strong correlation to the spring months (r = 0.66, p < 0.05), which is similar to what has been reported for *Abies guatemalensis* by Anchukaitis et al (2014) in northern locations of Guatemala.

A more recent study in the same area of Michoacan, Mexico with *Abies religiosa* showed similar results to that of Huante et al., (1991), finding significant positive correlations with previous October precipitation (Carlón et al. 2016). This finding is similar to past studies of *A.guatemalensis* in Guatemala that have shown significant correlations with previous October precipitation and radial tree growth (Anchukaitis et al., 2014). Other species in Guatemala like *Pinus oocarpa* in the eastern dry corridor of Guatemala show a significant positive correlation to precipitation from previous October as well (Szejner 2011).

The significant negative correlation reported by Anchukaitis et al., (2013) for the temperature of July of the current growing season using instrumental data is not present in any of these monthly or seasonal analyses. However, a significant negative correlation to the temperature of July from previous year was observed when analyzing the residual chronology against instrumental data (see Appendix B). Significant positive correlations similar to those described by Anchukaitis et al., 2013 between precipitation from February through March and the chronology are present in this analysis when assessing the climate sensitivity of the AR-standard chronology against the gridded GPCC v7 at 1.0°and CRU TS 3.34.01 data for the period 1903-2013. The importance of the influence from previous year climate on current year's growth has been widely reported (Fritts 1976, Briffa et al., 2002; D'Arrigo et al., 2004). Overall, it seems that the precipitation from previous June-October has an influence on the radial growth of *A. guatemalensis* in the Pacific basin of Guatemala. This local variation of climatic factors limiting radial growth of A. *guatemalensis* in the Pacific basin compared to the climate factors reported for Huehuetenango (Anchukaitis et al, 2013), could be the result of differences in micro-climate (Peterson et al., 2002; Dang et al., 2007; Hafner et al., 2015; Mattos et al., 2015). For instance, this could be an effect of soil moisture in the volcanic soils where *Abies guatemalensis* occurs in the Pacific slope of Guatemala functioning as a water reservoir.

The function of water reservoirs in the form of snow pack and their influence on the radial growth of *Abies lasiocarpa* has been studied before finding high correlations to previous year climate where water from the reservoir (e.g. late snowmelt) improved the length and quality of the growing season (Peterson et al., 2002). In other species (e.g. *Mimosa tenuiflora*) it has been found that plants use their accumulated water reserves from previous year to satisfy their demand for growth (Mattos et al., 2015). In this same study (Mattos et al., 2015), *M. tenuiflora* showed different climate sensitivities at different locations where it was study. The differences were explained as a function of differences in the beginning of the rainy season and the total rainfall of each year. This difference in climate sensitivity of a same species in different locations has been reported for *Abies religiosa* in different locations in Michoacan, Mexico (Huante et al., 1991; Carlón et al., 2016), for *Quercus robur* (Hafner et al., 2015), for *Pinus virginiana* and *Pinus rigida* (Copenheaver et al., 2002), and in Guatemala for *Pinus oocarpa* (Szejner 2011). The role of permeable volcanic soils as modulators of early wood growth acting as water reservoirs in this location should be assessed in future studies.

Climate data evaluation

The availability and longer records of monthly data interpolated from precipitation gauges (e.g. Schneider et al., 2015) might seem an obvious advantage to assess climate sensitivity of dendrochronological records where instrumental data is limited, but the spatial resolution does not necessarily capture the variability registered at a local level and seems dependent on the spatial resolution selected (Daly 2006, Hofstra et al., 2010; Pons et al., 2017). For instance, the recorded precipitation from the Zunil and Santa María weather stations in Quetzaltenango (Figure 4.11 and 4.12), separated by 4.34 km and 200 m.a.s.l from each other seem to capture the differences in precipitation between these two locations, but they both differ from the precipitation derived from the closest GPCC version 7 gridded precipitation data point at 0.5° (Schneider et al., 2016).

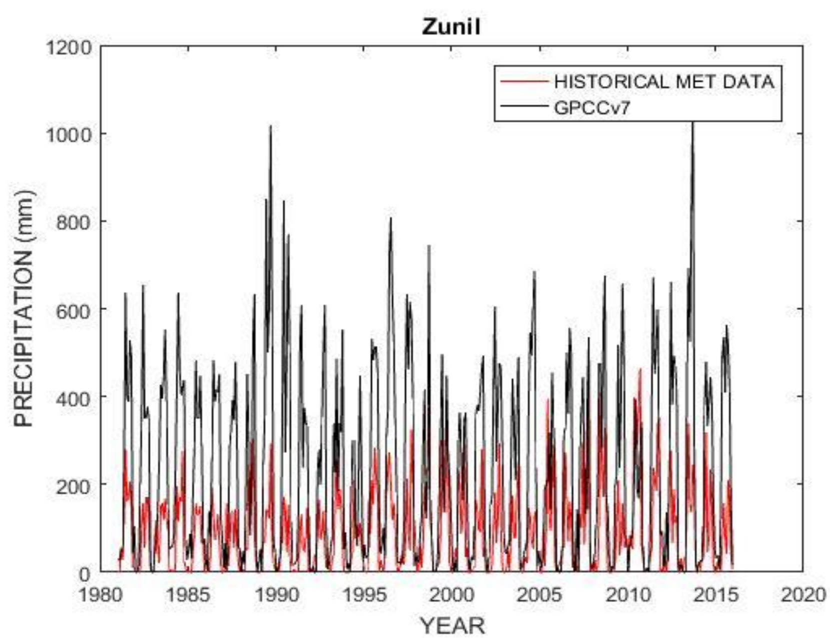

Figure 4.11.Historical precipitation data from the Zunil weather station (1980 -2015) against the same period of data from GPCC v7, 0.5° (Schneider et al., 2016; INDE 2017).

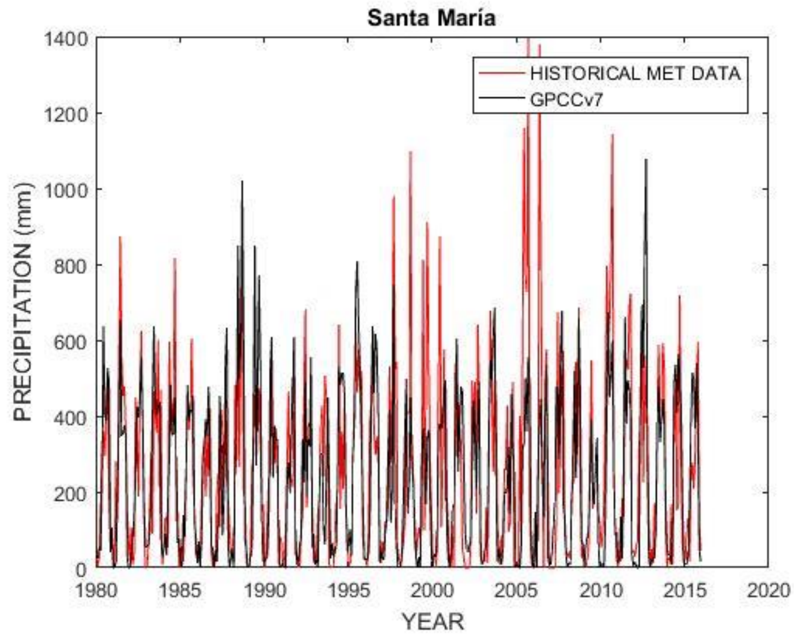

Figure 4.12. Historical precipitation data from the Santa María weather station (1980 -2015) against the same period of data from GPCC v7, 0.5° (Schneider et al., 2015: INDE 2017)

The variability observed in the amount of precipitation between the instrumental data and the gridded GPCC v7 at 0.5°, which resulted in an underestimation of precipitation in Zunil and overestimation or precipitation in Santa Maria, could explain in part the different results of the climate sensitivity evaluation between instrumental and gridded precipitation data of *A. guatemalensis* at this location. Although the GPCC data usually shows a dry bias in the wet season and a wet bias during the dry season (Karmalker & Bradley 2011), this is not the case for the Zunil precipitation records where the GPCC v7 at 0.5° data overestimates the whole period under evaluation (1980-2015). The same is true for the Labor Ovalle weather station (Figure 4.13). At this location, the highest precipitation on instrumental records extents to 400 mm while the GPCC v7 at 1.0° data surpassed the 800 mm.

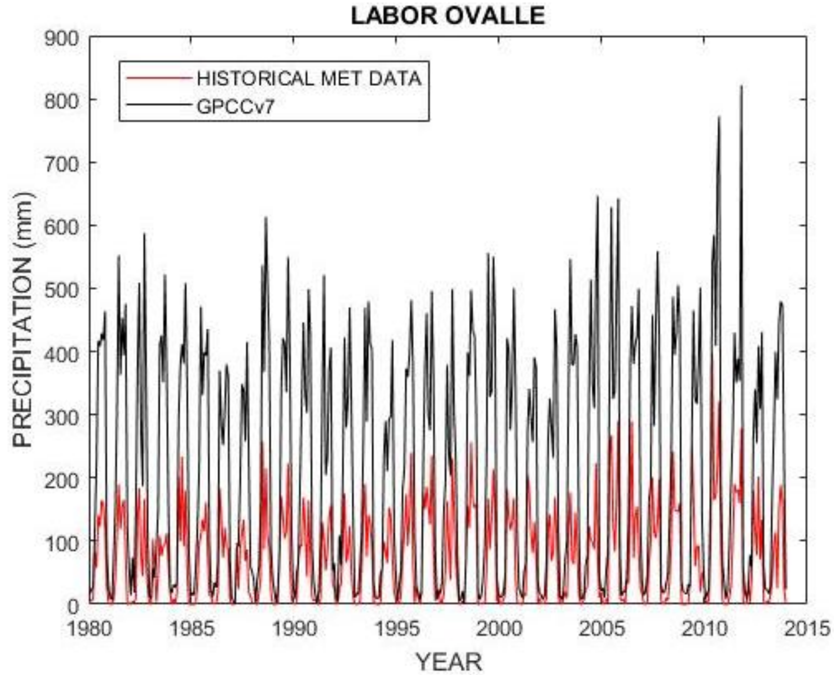

Figure 4.13. Historical precipitation data from the Labor Ovalle weather station (1980 -2014) against the same period of data from GPCC v7, 1.0° (Schneider et al., 2016; INSIVUMEH 2017).

This type of inconsistencies can be described for earlier time periods as well. A comparison between the Pensamiento weather station located in Quetzaltenango at 1,200 m.a.s.l. and the gridded GPCC v7 1.0 for the near grid point shows a difference in the amount of precipitation for the 1910-1947 period with an underestimation from the GPCC product regarding the amount of precipitation reported by the station (Figure 4.14). Comparing different instrumental records from stations at different locations and altitudes suggests that discrepancies between instrumental and GPCC precipitation records seem to be resolved or at least reduced when the station is located further south (away) from the mountainous region. For instance, La Mina weather station located at 1,340 m.a.s.l. shows less discrepancies in the amount precipitation (Figure 4.15) than the

Labor Ovalle (2,400 m.a.s.l.) and Zunil (2,316 m.a.s.l.). Similar results were obtained for La Moka at 1080 m.a.sl. (Figure 4.16).

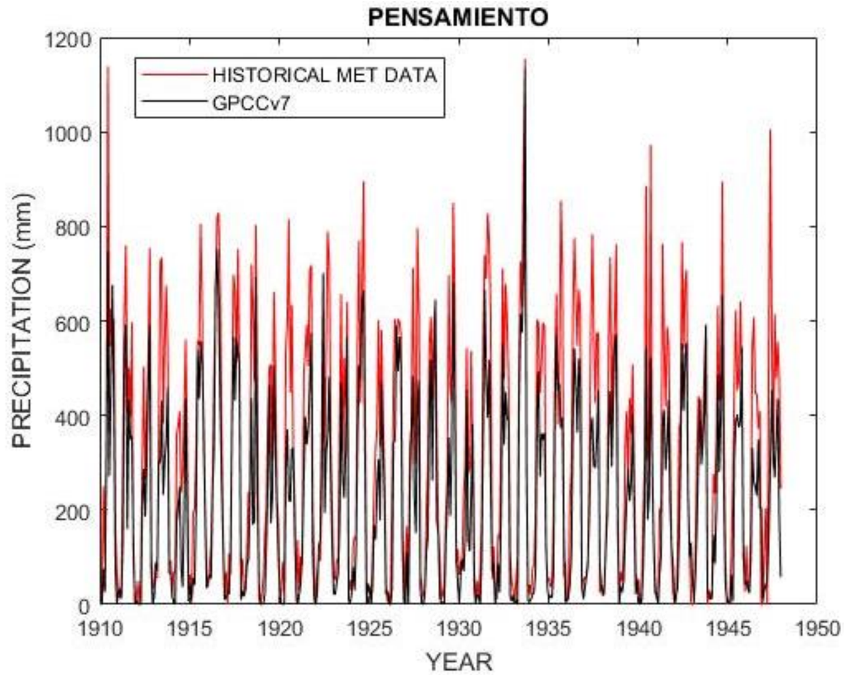

Figure 4.14. Historical precipitation data from the Pensamiento weather station (1910 -1947) against the same period of data from GPCC v7, 1.0° (Schneider et al., 2016; INSIVUMEH 2017).

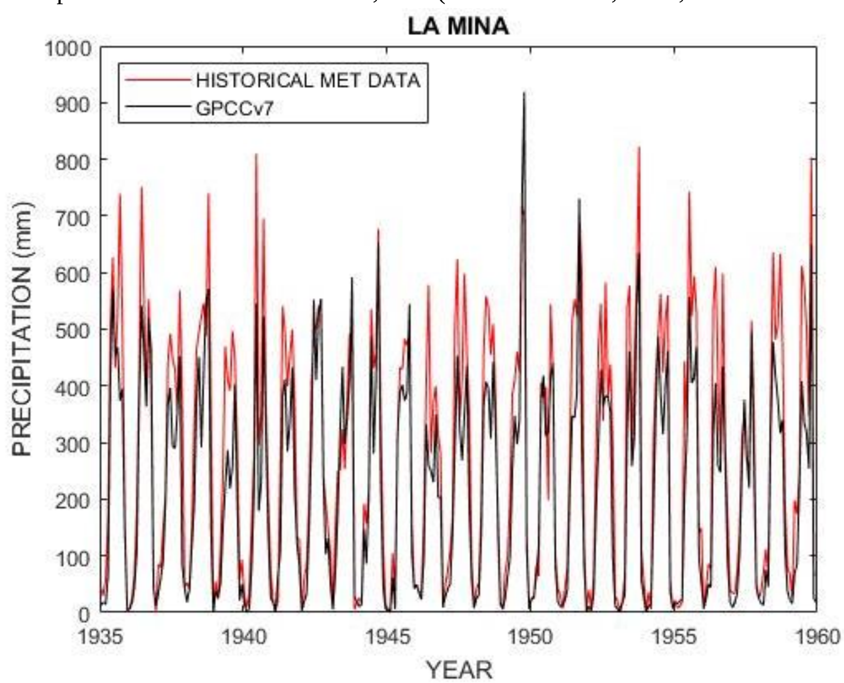

Figure 4.15. Historical precipitation data from the La Mina weather station (1935-1965) against the same period of data from GPCC v7, 1.0° (Schneider et al., 2016; INSIVUMEH 2017).

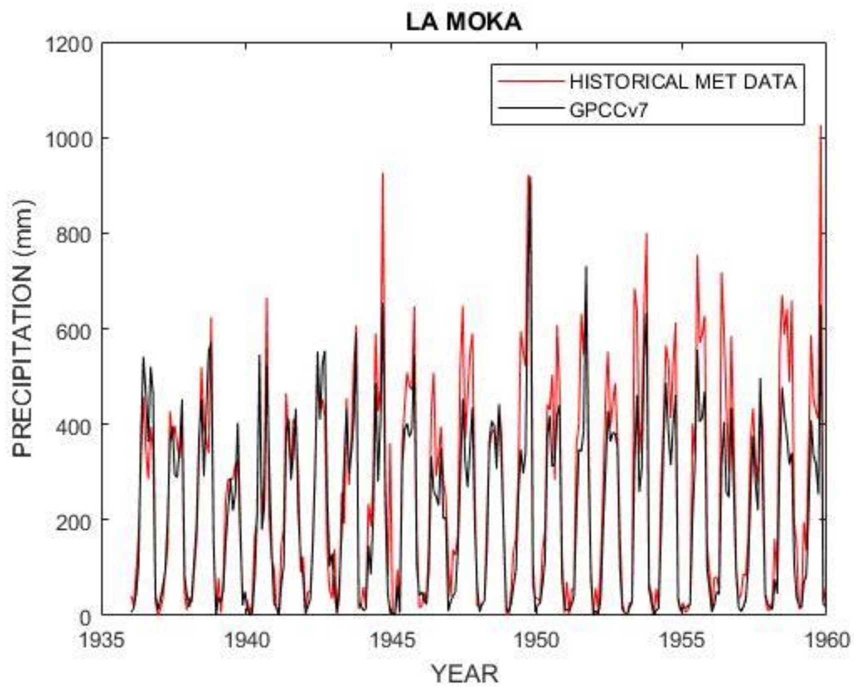

Figure 4.16. Historical precipitation data from the La Moka weather station (1936-1960) against the same period of data from GPCC v7, 1.0° (Schneider et al., 2016; INSIVUMEH 2017).

The deviations between the instrumental records and gridded precipitation GPCC v7 products for different time-periods at high elevation sites in complex mountainous regions of Guatemala is consistence with the literature that has pointed out that the coarse resolution of certain gridded products (e.g. GPCC) don't have the skills to resolve the complexity of the topography in these locations. These discrepancies not only could have an impact on the assessment of climate sensitivity studies in dendrochronology, but also during the transfer function when the magnitude of the precipitation is established. Aside from their use on climate sensitivity assessments, the differences between the two datasets could also impact risk assessment plans and adaptation strategies locally if the differences in the amount of precipitation are not assessed. In this particular region (upper Samalá River watershed), measuring the difference and quantity between precipitation up and down the hill is critical for managing the Santa Maria hydroelectric plant located near the Santa María weather station because it informs the expected peaks of the hydrograph and inundation level at the dam. If past drought periods were to be estimated by the GPCC products, caution is advised when estimating the quantity of precipitation for the high-altitude mountainous regions at this location. Although Schneider et al., (2014) have reported an increase in the number of weather stations incorporated for their use in gridded precipitation data sets, this does not coincide with other knowledge that the Central American and Caribbean domain are undergoing a decrease in the number of official weather stations (Giannini et al., 2001).

Reconstruction of June-July-August mean precipitation

After testing for different monthly composites and reviewing the coherence between instrumental and gridded precipitation records, I selected the previous year June-July-August mean precipitation from the Labor Ovalle weather station to calibrate the chronology. Precipitation from previous June-July-August was selected as the primary limiting factor for the model based on the statistical significance of the analysis of Pearson coefficients from the instrumental data and the consistency found among gridded and instrumental data for longer periods (1903-2013). Three validation statistics were calculated to assess the skills of the reconstruction; the root mean squared error (RMSE) the reduction of error (RE) and correlation coefficients (Cook et al., 1994; Fritts et al., 1990).The reported RMSE for the model is 9.4, which is a measure of the average size of the estimate error for the validation series. Because it is the original units of the precipitation data, it is comparable to the standard error of the estimate (Woodhouse &

Lukas 2006).The reported RE is 0.35 which suggest that the model has better skills than using the average to estimate past precipitation values.

Overall, the results suggest a high correlation for the calibration period (r= 0.50, p < 0.05) and a higher correlation for the whole period (r= 0.53, p < 0.01). The calibration and verification curves generated using instrumental data are shown in figure 4.17. A regression analysis performed between instrumental records of precipitation and the reconstructed values for precipitation shows a significant correlation (r^2 =0.27, p<0.01).

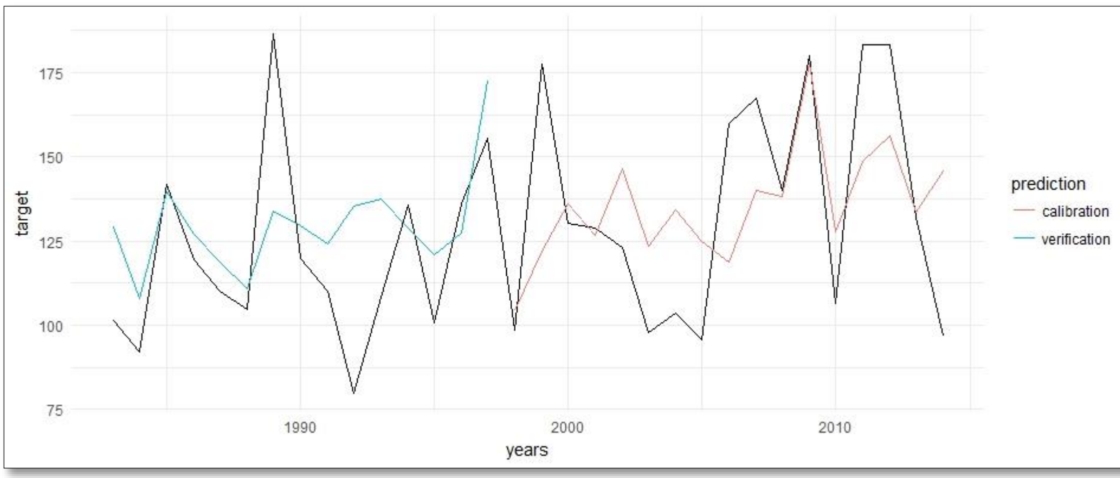

Figure 4.17.. Calibration and verification curves for the regression model generated using instrumental data for the Labor Ovale weather station.

The full reconstruction for the mean June-July-August period 1889- 2013 is shown in figure 4.18. The long-term average has been highlighted in red.

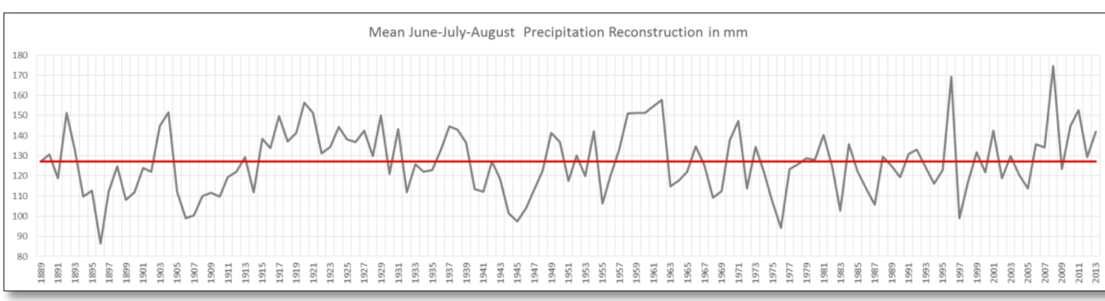

Figure 4.18. Precipitation reconstruction from *Abies guatemalensis* based on June-July-August from previous growing year (black) and long term average for the period 1889-2013 (red).

Some independent instrumental records from other official and private weather stations around the area were used for verification and validation of the reconstruction of precipitation for the mean June-July-August precipitation. For instance, the Cuatro Caminos weather station (period 1980-2013) located at 2,510 m.a.s.l shows a correlation of *r* = 0.54. The Totonicapán weather stations (period 1980-2013) located at 2,415m.a.s.l shows a correlation of *r* = 0.44. The Zunil weather station (period 1981-2013) located at 1,860 m.a.s.l shows a correlation of *r* = 0.52.

Also, historical archive instrumental records from the INSIVUMEH extending back to the beginning and mid-20th century show high correlations to our reconstruction of mean June-July-August precipitation. For instance, Quetzaltenango weather station (period 1928-1949) showed a correlation of *r* = 0.40, the Pensamiento weather station located at 1,256 m.a.s.l. showed a correlation of *r* = 0.20 for the period 1910-1947 against the same period of reconstructed mean June-July-August precipitation. Subsequently, Las Mercedes (*r* = 0.39, 960 m.a.s.l., period 1908-1917); Las Mercedes (*r* = 0.23, 960 m.a.s.l., period 1934-1947) and Palmira (*r* = 0.22, 1,160 m.a.s.l., period 1914-1947).

Some historical records from weather stations located near the coffee plantations within the Samalá River watershed also showed high correlations with the mean June-July-August reconstruction. For example, the El Nil weather station 1,360 (m.a.s.l.), located at a coffee farm in El Palmar showed a correlation of *r* = 0.37 for the period 1945-1950), the La Suiza weather station (*r* = 0.27, 1,020 m.a.s.l., period 1945-1959), the Beliz weather station (*r* = 0.20, 840 m.a.s.l., period 1934-1959). All of these stations were located in or around coffee farms (Figure 4.19).

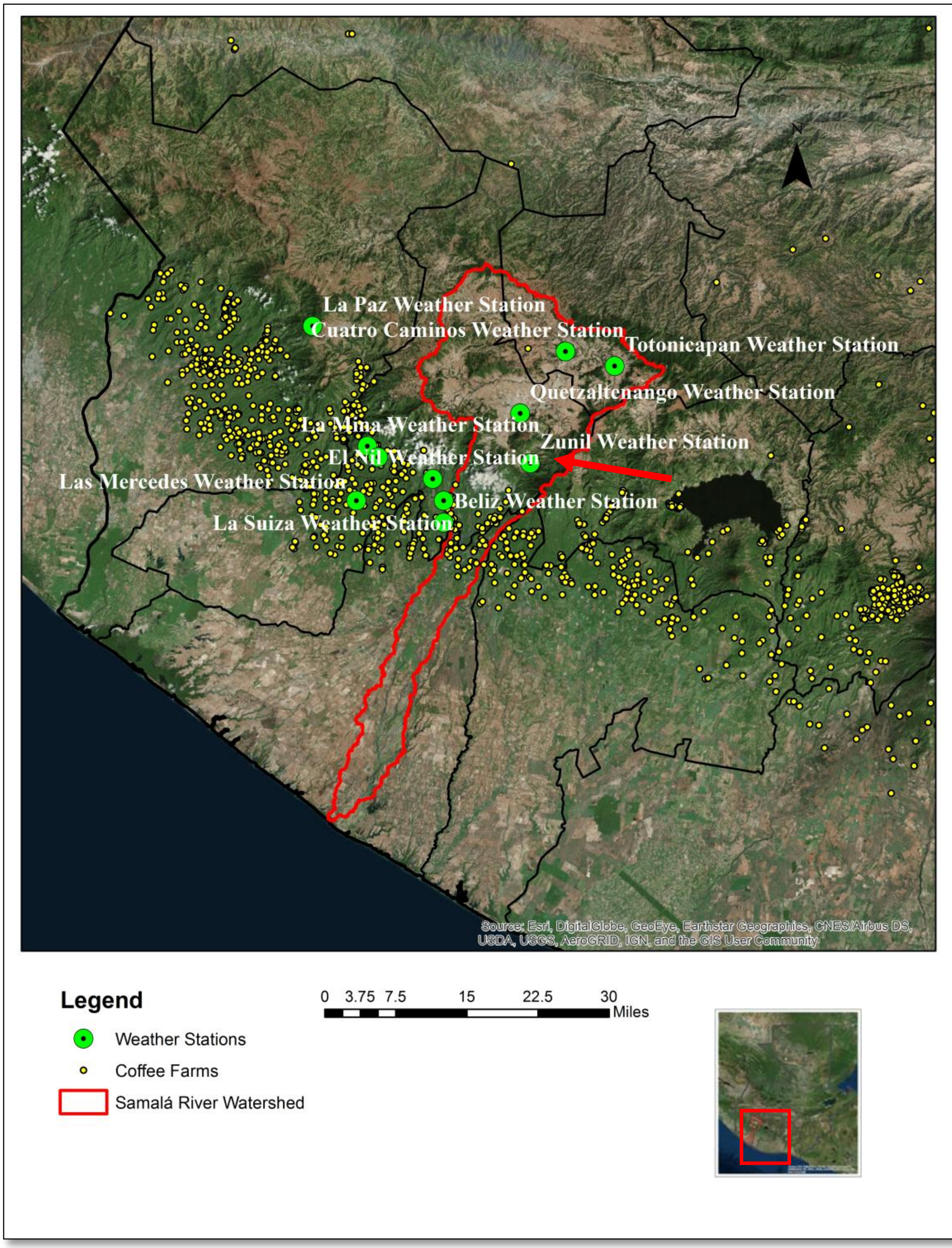

Figure 4.19. Location of weather stations showing correlations to the precipitation reconstruction record. A red arrow shows the reconstruction site in the middle of the stations. Yellow dots represent coffee farms near the area (Source: The author and CIAT 2012).

The verification process using the archive records from INSIVUMEH represents vital information that supports the hypothesis proposed here regarding the climate sensitivity of the chronology to mean precipitation from June-July-August because it shows a spatial correlation of weather stations against the reconstruction (Woodhouse 2001), but also because these correlations happen in the most important coffee regions of Guatemala. This spatial correlation also matches the official climate region defined by the INSIVUMEH based on long term precipitation and temperature patterns (Figure 4.20). The *bocacosta* climatic region highlighted in yellow in southern Guatemala shows a consistent pattern of climate that matches the sensitivity of the chronology to this area, supported by the correlations with the historical records from INSIVUMEH.

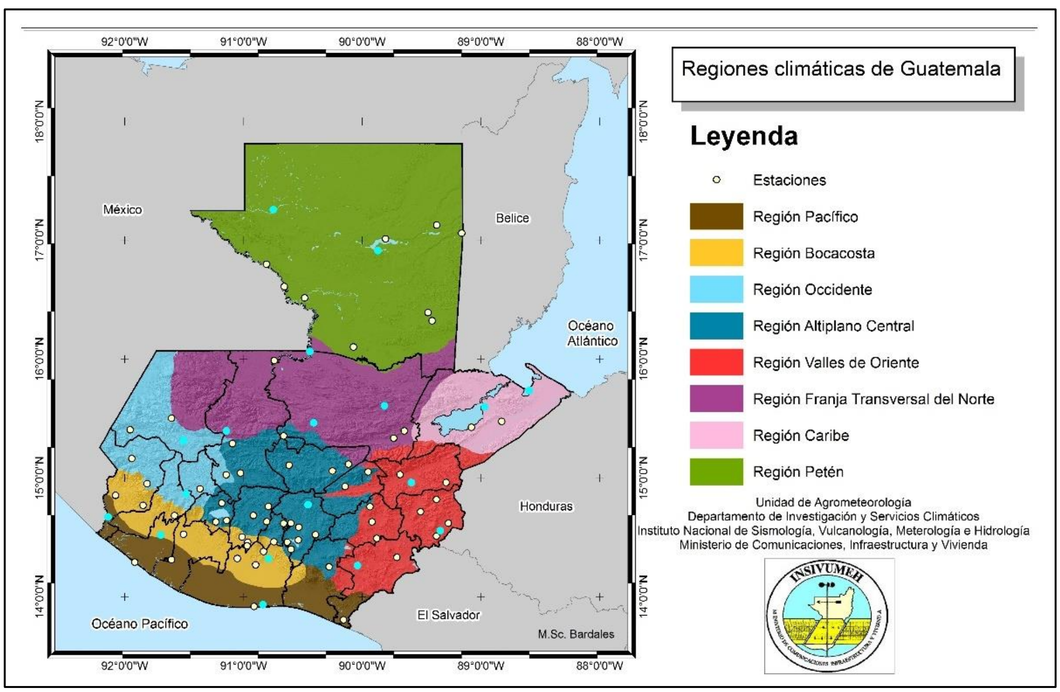

Figure 4.20. Climate regions of Guatemala defined by INSIVUMEH. The yellow region represents the *bocacosta* site where coffee grows. Source: INSIVUMEH 2017.

A frequency analysis of the reconstructed mean precipitation of June-July-August for the above and below long-term average (127.09 mm) for the period (1889-2013) is presented here (Table 4.1 and 4.2). For arrangement convenience, the data was analyzed starting in 1889 and ending in 2009.

Table 4.1. Absolute frequency of below long-term average precipitation for June-July-August reported for the 1889-2009 period based on 30-year conglomerates.

Dry Events	1890-1919	%	1920-1949	%	1950-1979	%	1980-2009	%	Total events period 1889-2009	% of total
1 year event	2	50	1	33.3	3	42.86	3	33	9	39
2-year events	0	0	0	0	1	14.29	4	44	5	22
3-year events	0	0	0	0	2	28.57	2	22	4	17
4-year events	0	0	1	33.3	0	0	0	0	1	4
5-year events	0	0	0	0	1	14.29	0	0	1	4
6-year events	0	0	0	0	0	0	0	0	0	0
7-year events	0	0	0	0	0	0	0	0	0	0
8-year events	1	25	0	0	0	0	0	0	1	4
9-year events	1	25	1	33.3	0	0	0	0	2	9
10-year events	0	0	0	0	0	0	0	0	0	0
***Total events**	**4**	100	**3**	100	**7**	100	**9**	100	**23**	100

According to the analysis, drier than average mean June-July-August precipitation is represented mostly by single year events (39%) followed by two and three-year consecutive dry events (22% and 17% respectively). Four events of 3 consecutive years under the average were recorded for 1963-65 and 1967-69 and two other events on 1985-87 and 1993-95. The reconstruction suggest a 4-year drought for the period 1932-35. A one five-year below the long term average event is suggested by the reconstruction in 1974-78. A single 8-year event was recorded for 1905-12 and two single 9-year events are suggested for the 1894-1902 and 1940-48 period. It is important to highlight that the 1940-47 dry period reported by Hastenrath and Polzin (2013) is represented here by one of the 9-year consecutive dry period (1940-48). Similarly, the 1971-78 dry period described by Hastenrath and Polzin (2013) is represented in our analysis in one of the 5-year period (1974-78) as seen in Table 4.1.

In relation to the wet periods (above long-term average precipitation), these seem to be different in terms of the distribution of frequencies. Although still dominated by single year events, these represent up to 62% of all the above long-term average. The 2-year events follow with only a 19% of the events for the whole period. The tree, four, five, six and 10-year events represent a 4% of the total events reported for the whole period (1889-2009). The only 3-year event is suggested for the years 2006-2008. Subsequently, the only 4-year event is reported for the 1936-39 years; the 5-year event for 1915-19 years; and the 6-year event for the 1957-62 years. During the 5-year event reported here, the *Fumagina sp.* coffee fungus appeared in coffee farms in our study area in Quetzaltenango (Dominguez 1970). The 10-year event was reported for 1920-29. All these events are shown in Table 4.2.

Table 4.2. Absolute frequency of above long-term average precipitation for June-July- August reported for the 1889-2009 period based on 30-year conglomerates.

Wet Events	1890-1919	%	1920-1949	%	1950-1979	%	1980-2009	%	Total events period 1889-2009	% of total
1 year event	2	40	2	50	6	75	6	67	16	62
2-year events	2	40	0	0	1	12.5	2	22	5	19
3-year events	0	0	0	0	0	0	1	11	1	4
4-year events	0	0	1	25	0	0	0	0	1	4
5-year events	1	20	0	0	0	0	0	0	1	4
6-year events	0	0	0	0	1	12.5	0	0	1	4
7-year events	0	0	0	0	0	0	0	0	0	0
8-year events	0	0	0	0	0	0	0	0	0	0
9-year events	0	0	0	0	0	0	0	0	0	0
10-year events	0	0	1	25	0	0	0	0	1	4
***Total events**	**5**	100	**4**	100	**8**	100	**9**	100	**26**	100

Similarly to the dry events discussed before, the wet events display some similarities with the enhanced rainfall regimes described by Hastenrath and Polzin (2013) and with some pluvial events reported by Herrera et al., 2017. For instance, the 1931-1938 period suggested by Hastenrath and Polzin (2013), matches one of the 4–year events reported here (1936-39). During this 4-year pluvial event, several pests (e.g.

Mycena citricolor, Ceratocystis fimbriata) were reported for coffee crops in Quetzaltenango near our study area, which are associated with high humidity. In fact, up to a hundred thousand quintals of coffee were lost in the decade of the 1930's as a direct result of the occurrence of *Mycena citricolor* (Dominguez 1970). The 1957-62 period suggested here as a 6-year above the average event has been reported by Herrera et al., (2017) for the 1958-62 similar period. Another pluvial multi-year event reported by Herrera et al, (2017) is that of 1977-81, which coincides with a 3-year event in our chronology for the years 1979-81. Similarly, another wet spell during 2006-08 identified in our reconstruction partially matches the one reported by Herrera et al., 2017 for the 2007-09 years. Herrera et al., (2017) generated a high-resolution atlas for the Caribbean domain using a Palmer Drought Severity Index (PDSI). The atlas goes back to 1950. The comparisons made here are based on the generalizations for Guatemala suggested in the document and more in-depth analysis is recommended on a pixel by pixel assessment.

Precipitation-ENSO teleconnection

The periodogram for the standard chronology is shown in the figure 4.21. The spectral analysis from the long time series suggest that more than 20% of the variance is explained by a 0.1 bandwidth indicating a strong decadal signal followed by a signal around a 25-year cycle that explains up almost 19% of the variance. A 3.7-year cycle is also reported in this analysis explaining around 13% of the variance. This last period could correspond to a potential ENSO bandwidths. The correlation analysis between the *A. guatemalensis* chronology and a seasonal June-July-August an Oceanic Niño Index

(ONI) for the ENSO 3.4 SST region covering the 1950-2013 yielded a negative correlation (r = -.29).

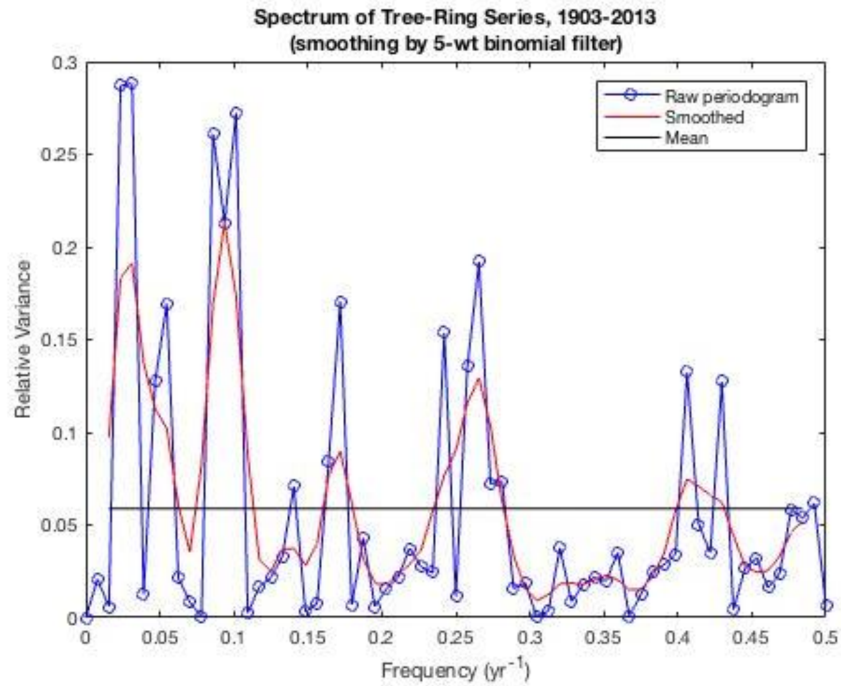

Figure 4.21. Spectral power of the chronology form *Abies guatemalensis* for the period 1903-2013

Subsequently, a May-June-July ONI for the ENSO 3.4 SST region covering the 1950-2013 period suggest a negative correlation of r = -0.27. This is one of the most important findings of the first part of the study because it enables the understanding of the mechanisms that regulate precipitation at this location in the Pacific slope of Guatemala. If the information generated here could be integrated into a model to predict precipitation of June-July-August for at least two months in advance it could help agriculturalist better prepare for one of the driest periods within the wet season in the region. Anchukaitis et al., (2013) reported similar correlations to an ENSO 3 index (r = -0.44). Teleconnections between ENSO and tree growth have been reported in several studies in this tropical region (Huante et al., 1991; Díaz et al., 2001; Villanueva-Díaz et al., 2005: Anchukaitis et al., 2014; Carlón et al., 2016). These findings are consistent with the ENSO-related precipitation influence described for the region, but become more relevant as they start to point to regional and local scale variability supported by the correlations found in this study (Hastenrath 1976; Diaz & Markgraf 1992, Giannini et al., 2000; Giannini et al., 2000; Karmalkar & Bradley 2011; Steinhoff et al., 2014).

Conclusions

This research has demonstrated successful cross-dating and climate sensitivity of *Abies guatemalensis* in the Pacific slope of Guatemala. Therefore, *A. guatemalensis* in this location can be used in dendroclimalotogy studies to expand climate records in the region. The climate sensitivity of the species was evaluated against local instrumental and regional gridded climate data which suggest that, depending on the spatial resolution and length of the GPCC v7 gridded precipitation data selected, the climate sensitivity correlations can vary when compared to 30-year instrumental data. Aside from missing values, the quality of available instrumental records is hard to evaluate and the short span of the records limits the evaluation of long-term (e.g. 1903-2013) gridded products against instrumental records. The verification analysis of historical instrumental data against GPCC v7 precipitation records at different spatial resolutions (1.0° and 0.5°) at different altitudinal gradients suggest that deviations between instrumental and gridded data sets are larger at high-altitude mountainous regions. Given this situation, the use of one or other set of climate records (or a combination of both) should be ultimately examined by the researcher to match the study requirements. For instance, the GPCC v 7 gridded data is not recommended to estimate the total amount of precipitation at this locations, but could be useful when analyzing trends.

In this study I selected the monthly and seasonal correlations that remained consistent among the different climate records and evaluated the potential of *A. guatemalensis* as a climate proxy in the Pacific of Guatemala producing a longer record of precipitation in this agriculturally important region that extends from 1889 to 2014. In this region of Guatemala, *A. guatemalensis* radial growth can be used to reconstruct precipitation from June-September from previous year. Temperature apparently has little influence on determining the radial growth of the species in this region. The study suggests that the June-July-August mean precipitation in the upper Samalá River basin partially determines the growth of *A. guatemalensis*. The precipitation from previous June-September seems to have the greatest influence on early wood formation of *A. guatemalensis* in this location. Yet, this hypothesis needs further research and was not assessed during this study because early wood and late wood were not evaluated independently. In terms of the usefulness of our precipitation reconstruction, the records of mean June-July-August precipitation generated in this study are relevant to agriculture and hydropower production in the region because the biggest decline in rainfall projected for the Central American and Caribbean domain is expected to occur during the boreal summer months for June, July and August at this location (Rauscher et al. 2008; Campbell et al. 2011; Karmalkar et al. 2011; IPCC 2014). In fact, the mid-summer drought occurring in mid-July and August is expected to decline in 26% in the Pacific of Guatemala (Maurer et al., 2017). The long-term perspective of our continuous precipitation reconstruction validated with historical instrumental records within the coffee growing areas could illustrate past coffee crisis and the effects of precipitation on coffee productivity (e.g. *via* relationships with pests and infestations as discussed in the following section) and put in perspective the historical frequencies of droughts and pluvial events. To this respect, the mean precipitation from June-July-August at this location seems to be influenced by the SST in the Pacific Ocean in the form of ENSO in the region 3.4. This inverse relationships between May, June and July seasonal ONI index to the mean precipitation in June-July-August could be used as an early warning system by agriculturalist in the region to assess the potential precipitation expected during the months when the mid-summer drought is active.

Our analysis on the frequency of above and below long-term average events suggest that single year droughts dominate the record (39%), yet two and three-consecutive year droughts are not unusual (22% and 17% of the record respectively). The early part of the reconstruction also suggest a 9-year and 8-year drought events during the 1894-1902 and 1905-12 respectively. This information should be taken into account by stakeholders including agriculturalist and hydropower production managers in the region regarding adaptation strategies to future droughts that could extent up to nine consecutive years. Equally important in this region are the pluvial events because precipitation extremes in the form of excessive rainfall have had an impact on agriculture, infrastructure and the overall quality of life of the residents within the Samalá River watershed (Soto et al., 2015). To this respect, single year events also dominate the evaluated period (1889-2009) with 62 % of the total events, but these were not closely followed by the two-consecutive year events (19%). This information can be taken into account for risk management plans regarding the interactions of precipitation and volcanic activity in the form of lahars. In this case, the 3, 4, 5, 6, and 10-year events represent only a 4% of the total pluvial events. It is important to highlight that during one of the 5-year pluvial event reported in our reconstruction (1915-19), a fungus outbreak of *Fumagina sp*. infected the coffee plantations in our study area. Similarly, during the 10-year pluvial event (1920-29), another fungus associated with high humidity (*Mycena citricolor)* devastated the coffee plantations in the area. During a 4-year pluvial event reported in our reconstruction 1936-39, the *Ceratocystis fimbriata* fungus attacked coffee plants. Our reconstruction also suggests an above-average precipitation during the outbreak of coffee leaf rust (*Hemileia vastatrix*) in 2010-2013. Hence, knowing the frequency of these events is relevant for coffee productivity and suggest that 4 or more consecutive periods of above-average precipitation can be associated with coffee pests and subsequently great economical losses. Yet, given the multi-factorial nature of pests and infestations, in-depth analysis are needed to assess the overall influence of climate.

The *A. guatemalensis* forest stand in Kanchej is at risk of disappearing due to human pressures that include harvesting the wood and twigs for Christmas crowns and trees (De Urioste-Stone et al., 2013). Studies have shown that precipitation is a main driver of biodiversity in *A. guatemalensis* forests and the scenario of decreasing future precipitation should be consider a threat to it (González & Castañeda 1983). Future studies should focus on early and late wood formation and their relation to climate from previous and current growing years.

CHAPTER FIVE

MULTI-DECADAL STREAMFLOW RECONSTRUCTION IN THE UPPER SAMALÁ RIVER BASIN, GUATEMALA.

Introduction

The Samalá River basin has been recognized for having one of the highest incidences of natural disasters in Guatemala related to annual flooding events by the Samalá River in combination with activity from the Santiaguito volcano causing lahars (a destructive mudslide) in the upper-middle section (UNESCO 2003; Soto et al, 2015). It is home to 120 settlements including department capitals, cities, towns and agricultural land. The population exposed to these disasters has been estimated to be around 350,000 (UNESCO 2003). The Samalá River has also been identified by local communities as essential for vegetables production and electric power production (De Urioste-Stone et al., 2013), however the frequent lahars within the watershed have caused damage to settlements, infrastructure and agriculture in the region, especially to coffee plantations (Rose 1987a Soto et al., 2015). For instance, at the end of June and beginning of July of 1983 during the rainy season and after an El Niño-Southern Oscillation (ENSO) event, a lahar destroyed 35% of El Palmar town and in a later event in August of 1984, the entire town was destroyed. In August 25th and 26th of 1988 another similar event caused serious damage to the Pan-American Highway and coffee plantations (Acajabón 1973;

DesInventar 2017). Once more, in August 28th1993, another lahar destroyed the CA-2 road and several coffee farms (Conde Carpio 2000). According to Viera (2003) the total area affected by lahars within the basin incremented from 0.077 km^2 in 1964 to 1.23 km^2 in 2001. Increasing moisture availability could promote ENSO-related precipitation variability on regional scales (Taylor et al., 2011). Whether the reported increase in lahars within the Samalá River watershed has been influenced by ENSO (during La Niña events) can only be addressed with a long-term record of local effects of the climate mechanisms affecting the region.

Because of the dramatic consequences of these disasters, the nature and occurrence of increased streamflow and lahar events needs to be studied, its variability addressed and the forcing mechanisms behind it understood. It is clear that mitigation and protection against these natural events should take into account the scientific analysis of existing data to be included in the risk management plans to minimize the devastating effects of this events. Yet, in Guatemala streamflow data (as most of the hydroclimatic data) is scarce, hardly accessible and when it does exist it usually doesn´t exceeds a few decades of data (Soto et al., 2015; Pons et al., 2017). Given this scenario, we use a tree ring chronology from the Kanchej forest in Quetzaltenango to reconstruct the hydrologic variability of the upper Samalá River basin (Malevich et al., 2013). Tree ring records have proven a useful proxy to extent hydroclimate records were instrumental ones are scarce, including those used in designing water infrastructure (Woodhouse 2001; Loáiciga 2005;Woodhouse & Lukas 2006; Meko et al.,2012 ; Mundo et al., 2012 ; Malevich et al., 2013; Villanueva-Díaz et al., 2014).

In order to assess the climate sensitivity of the chronologies, I used a similar approach to that used by Woodhouse 2001. The aim of this study is to provide a long record of the Samalá River streamflow that can be used to assess the natural variability of the discharge, to better understand the effects of mechanisms behind hydroclimate in the region and put the current trends in a historical perspective. This information could help decision makers from different sectors including agriculture and hydroelectric production within the watershed to adapt to future similar scenarios.

Methods

Study site

The Samalá River watershed covers 1,500 km² across the departments of Quetzaltenango, Retalhuleu and Suchitepéquez (Figure 5.1). Located between Santiaguito and Santo Tomas volcanoes, it follows the Zunil Fault Zone to the south (Bennati et al., 2011). Geologically, the area encompasses igneous and metamorphic rocks in the upper watershed and quaternary alluviums on the coastal plain. The average annual precipitation within the watershed ranges from around 2,000 mm at the top and coastal zones and displays the highest precipitation regime in the middle altitudes near San Felipe Retalhuleu with up to 5,500 mm drawing a bimodal distribution with peaks occurring in June and September (MAGA 2001). The average annual temperature ranges from 10ºC at the highest elevation to 25.5ºC at the coastal planes (MAGA 2002). The *A. guatemalensis* tree used here as a climate proxy is distributed across the high mountain range in Quetzaltenango and Sololá departments from 2700 to 3600 m.a.s.l.. These two departments are crossed by the Sierra Madre mountain range creating high elevation and cold temperatures associated with the presence of the species (González & Castañeda 1983). This complex topography creates an altitudinal change that gives room to a wide variety of microclimates allowing for diverse agricultural products, of which coffee is the most important.

Figure 5.1. Study location in southern Guatemala. The Samalá River Watershed is highlighted. Sampling location is indicated by a green star located at 14°46'39.68"N, 91°26'17.94"W at 3,300 m.a.s.l. and coffee growing areas are emphasized in gray. Source: Pons et al., 2017.

Tree-ring Data

I collected two to three increment core samples from 60 trees following the site, stand and tree selection described by Cook & Kairiukstis (1990) at the Kanchej forest near Quetzaltenango. A first set of samples was collected in the boreal summer of 2014 and a second one in the boreal summer of 2015. Samples were dried, mounted, and sanded. Skeleton plots were created from each sample following the cross-dating procedure described by Stokes & Smiley (1968), which allows for visual cross-dating and an initial dating for the samples. Some samples were excluded because highly growth-suppressed sections prevented measurements of ring widths (Stahle et al., 2011). The samples were measured to 0.001mm precision using a Velmex measuring table and the MJ2X software. The samples were then cross-dated and verified for adequate statistical correlations among samples and climate sensitivity using COFECHA (Holmes, 1983). After the cross-dating, I used the program ARSTAN (Cook 1985) to standardize and detrend the ring-width series using a 50 year smoothing spline to 50% amplitude of the individual series length. This de-trending function was tested for each of the samples during an interactive process to verify the adequate removal of non-climatic factors in the tree series. The AR-standard chronology (Cook 1985) was used to preserve the autoregressive structure of the time series to assess climate variability (Anchukaiti et al., 2014).

Streamflow data

The Samalá River watershed covers around 1,500 km^2 including the second largest city in Guatemala, Quetzaltenango and 119 other urban settlements (INE 2017).

The streamflow of the Samalá River is regulated at the upper-middle part of the basin by the Santa María hydroelectric power plant and then flows to the Pacific Ocean providing water for coffee processing and sugar cane irrigation among other uses. The INDE (National Electrification Institute) collects pre-dam streamflow data from the upper Samalá River data at a gauge located at 14°43’20.79″N, 91°31’22.34″W for the purpose of estimating discharge peaks and controlling hydropower generation. The precipitation captured by a local weather station (Labor Ovalle), shows a bimodal distribution with a very clear mid-summer drought during July-August (Figure 5.2). The difference between the annual distribution of precipitation and the one produced by streamflow measurements are likely an effect of different processes like precipitation, topography, soils, and evapotranspiration over an extended area that are incorporated in discharge measurements (Figure 5.3).

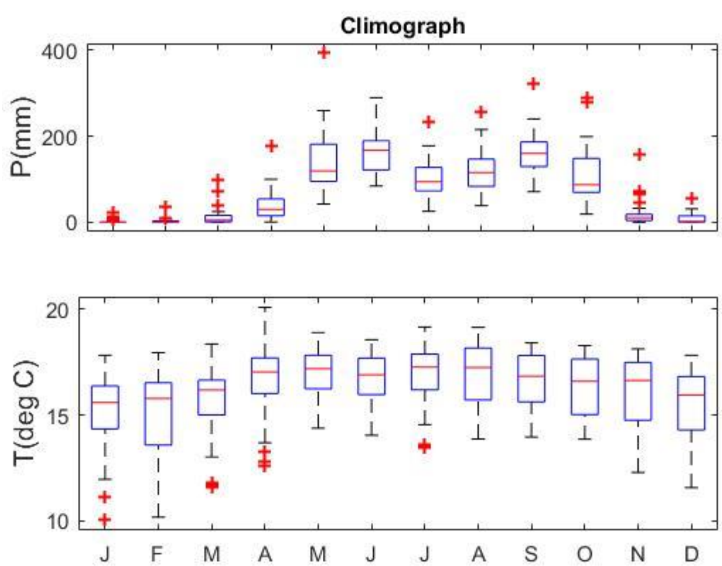

Figure 5.2. Monthly precipitation from the Labor Ovalle weather station. Source: INSIVUMEH 2017.

The discharge shown in the hydrograph for the period 1980-2015 is characterized by a subtle bimodal regime with a first peak in June and a second highest during October with the maximum coefficient of variation during October as well (Figure 5.3). The mid-summer drought, although present, has been probably smoothed out by interactions with soil across a large area of catchment, evapotranspiration and accumulated runoff. The mean annual accumulated streamflow recorded at this location is 74.53 m^3/s with an instrumental maximum of 132.74 m^3/s in 2005 and a minimum of 36.98 in 1997. In this study, low streamflow is defined as below-average discharge and high streamflow as above-average discharge.

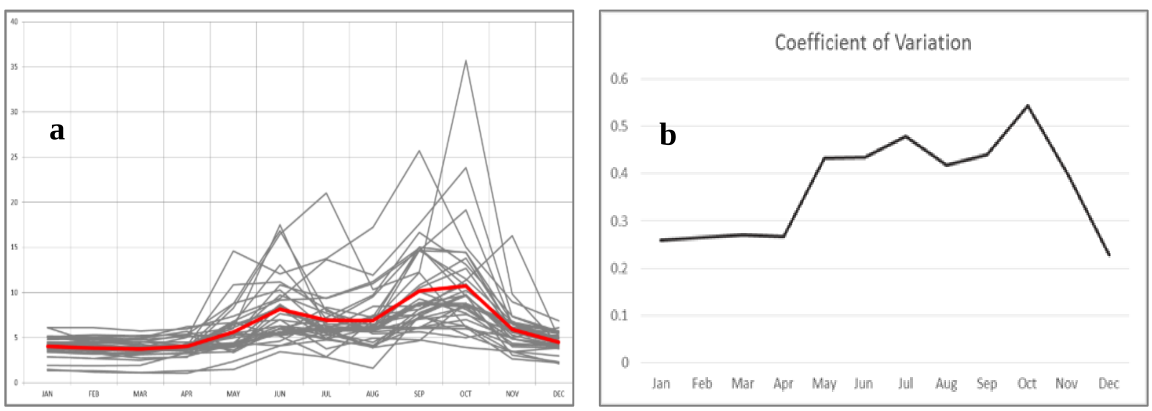

Figure 5.3 (a) Monthly average discharge (red) period 1983-2015 and (b) the respective coefficient of variation. Source: INDE 2017.

Climate sensitivity assessment

In order to identify potential relationships between the Samalá streamflow and tree-ring radial growth, I computed Pearson correlation coefficients between the standard chronology and the monthly Samalá River streamflow records using the Dendroclim 2002 program (Biondi & Waikul 2004). The streamflow data covers the period 1980-

2015 with no missing values. I used a 15 month window to explore previous year streamflow correlations to tree ring widths. The use of a window of 12 or more months is usually recommended when evaluating climate sensitivity (Meko et al., 2011) because radial growth could be associated with previous year (-1) climate (Fritts 1976). This autoregressive structure could reflect the multiyear hydroclimatic influence on the radial growth (Case & MacDonald). After the first assessment of individual correlations using Dendroclim, I used the *seascorr* function in the program R to evaluate seasonal correlations (Zang 2016). This function is based on the *seascorr* function generated for MATLA by Meko et al., (2011). The monthly composites evaluated here corresponded to 1, 3 and 6 monthly composites.

Streamflow reconstruction

In locations where tree growth might be limited by a single hydoclimatic factor (e.g. streamflow) a linear regression can be successfully used to reconstruct climate (Biondi 1997). In this study I used ordinary least squares (OLS) as a linear regression model to reconstruct streamflow records. I used the *skills* function of the Treeclim program in R to determine the reconstruction skills using split-calibration. In this type of analysis, a general exploration between climate variables and growth is assed followed by the selection of the strongest ones used later in reconstruction purposes (Zang and Biondi 2015). Three validation statistics were calculated to assess the skills of the reconstruction; the root mean squared error (RMSE) the reduction of error (RE) and correlation coefficients (Cook et al., 1994; Fritts et al., 1990). When possible, reconstructed streamflow records of high discharge were validated with historical documentation.

Periodicity analysis and ENSO correlations

The function *seascorr* in the program Matlab was used to examine the spectral properties of the reconstruction (Meko et al., 2011). After this first approach, a Pearson correlation analysis was performed between the tree-ring index and Oceanic Niño Indices (ONI) to evaluate potential relationships.

Results and Discussion

Tree-ring Data

The anatomic characteristics of *Abies guatemalensis* in this region are similar to those reported by Anchukaitis et al., (2013). Some samples showed local absent rings, cellular damage as well as micro-rings. Several growth-suppressed sections, usually present in the last 30 years, prevented further ring counting in most of the samples from the northwest aspect of the mountain. This has been recently reported for the same species in Guatemala (Anchukaitis et al., 2013).

The reported interseries correlation and mean sensitivity of our chronology are 0.447 and 0.273 respectively (Fritts, 1976; Holmes, 1983) which allows for the carrying out of climate analysis and reconstructions (Anchukaitis et al., 2013). The mean segment length for this subset of sample is 107 years, which could be extended in the future with more sampling. The coherence of the chronology was assessed using the Expressed Population Signal (EPS) for the standard chronology (Grissino-Mayer 2001) and the total length of the reconstruction was constrained by EPS >0.7. The standard chronology is shown in figure 5.4.

Climate sensitivity

The highest Pearson correlation was found between the tree-ring chronology and the mean monthly streamflow from August (r =0.46, p < 0.05) and September (r =38, p <0.05) from the previous year (Figure 5.5).

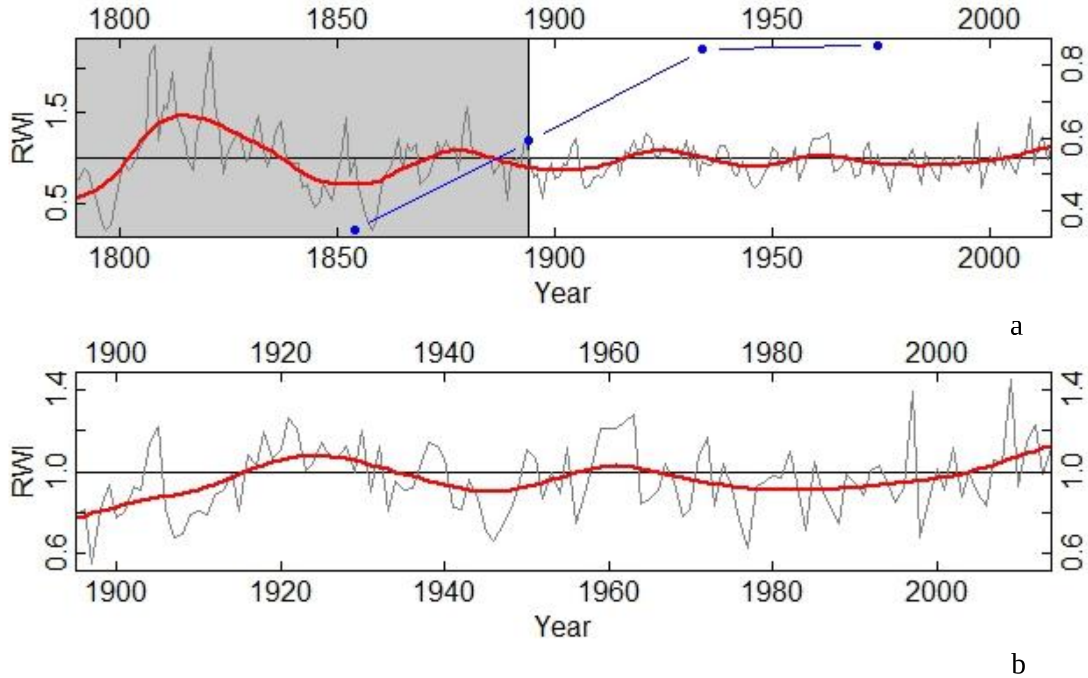

Figure 5.4. (a) Standard chronology from *Abies guatemalensis* showing the EPS cut at 1889 and (b) final standard chronology.

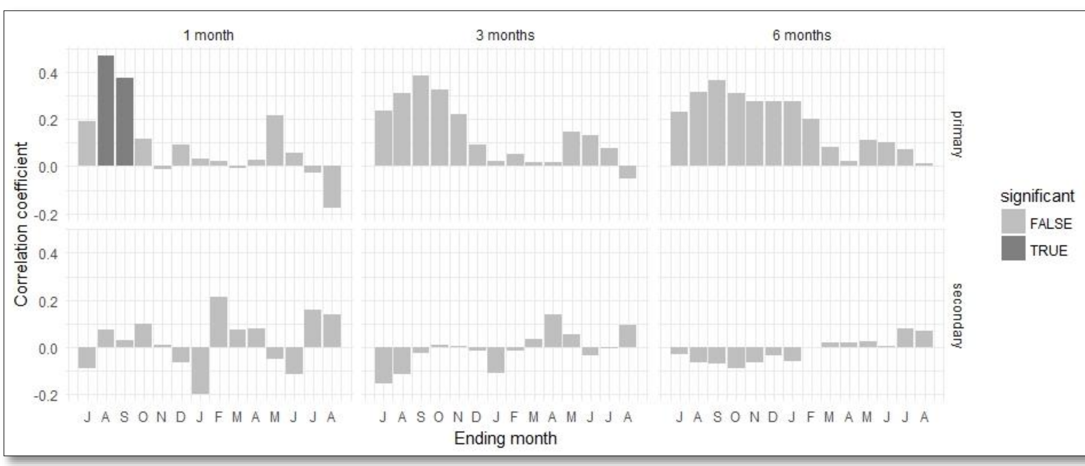

Figure 5.5. Seasonal correlation analysis for mean August-September-October streamflow.

Streamflow correlations to previous year growth have been reported for *Pinus mariana* in Canada (Case & MacDonald 2003) for *Pseudotsuga menziesii* (Villanueva-Díaz et al., 2005) reconstructing winter-spring discharge in Mexico and for *Araucaria araucana* and *Austrocedrus chilensis* to reconstruct October-June mean streamflow in Argentina (Mundo et al., 20120) among others (Villanueva-Díaz et al., 2014). Our results suggest that the streamflow reconstruction is potentially incorporating the interaction between the topography, infrastructure, soils, precipitation and evapotranspiration at regional scales, but also cyclonic precipitation (Case and MacDonald 2003; Laiciga 2005). A precipitation gauge near the tree-ring reconstruction site shows a high correlation with June-July-August from previous year precipitation, suggesting a potential lagged influence of precipitation from previous months and/or the incorporation of current-year precipitation into the discharge measurements.

Streamflow reconstruction

Based on the statistical significance of the analysis of Pearson coefficients from the instrumental data and after testing for statistical significance with seasonal composites, I selected mean streamflow from previous August-September-October to generate a simple inverse regression model using the tree-ring measurements from the upper Samalá River watershed. I generated a split sample calibration and validation model (Michaelson 1987) using 50% of the available years for each of the processes using the function *skills* from Treeclim (Zan & Biondy 2015). I selected the ordinary least squares (OLS) as the type of regression model to be developed (Cook et al., 1994). Mean August-September-October discharge was selected as the primary factor for the model. Three validation statistics were calculated to assess the skills of the reconstruction; the root mean squared error (RMSE), the reduction of error (RE), and correlation coefficients (Cook et al., 1994; Fritts et al., 1990).

The reduction of error (RE) reported for the model is 0.07, suggesting that the model has better skills than using the average as an estimator for previous streamflow estimates. The root mean square error (RMSE) however was low (2.07), which is a measure of the average size of the estimate error for the validation series. Because it is represented in the original units of the precipitation data, it is comparable to the standard error of the estimate (Woodhouse & Lukas 2006). Overall, the results suggest a correlation for the calibration period of $r = 0.39$ ($p < 0.05$) with a reduction of the skills for the whole period of $r= 0.32$ $p < 0.05$). The calibration and verification curves generated using instrumental data are shown in figure 5.6. A correlation analysis performed between the instrumental streamflow records and the reconstructed ones using this model shows a correlation between the data sets ($r= 0.34$, $p < 0.05$).

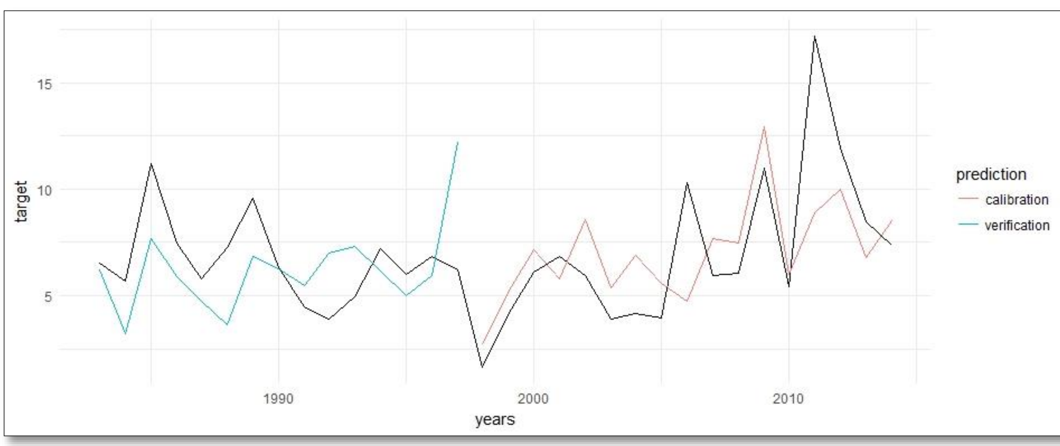

Figure 5.6. Calibration and verification curves for the regression model used to reconstruct mean streamflow from previous August-September-October events.

The multidecadal reconstruction of mean August-September-October discharge in the Upper Samalá River suggests that lower than mean streamflow for these months is presented mostly as single year events (39%) followed by two and three-year consecutive dry events (22% and 17% respectively) for the period 1889-2009 (Table 5.1).

Table 5.1. Absolute frequency of below long-term average streamflow for August-September-October reported for the 1889-2009 period based on 30-year conglomerates.

Dry Events	1890-1919	%	1920-1949	%	1950-1979	%	1980-2009	%	Total events period 1889-2009	% of total
1 year event	2	50	1	33	3	43	3	33	9	39
2-year events	0	0	0	0	1	14	4	44	5	22
3-year events	0	0	0	0	2	29	2	22	4	17
4-year events	0	0	1	33	0	0	0	0	1	4
5-year events	0	0	0	0	1	14	0	0	1	4
6-year events	0	0	0	0	0	0	0	0	0	0
7-year events	0	0	0	0	0	0	0	0	0	0
8-year events	1	25	0	0	0	0	0	0	1	4
9-year events	1	25	1	33	0	0	0	0	2	9
10-year events	0	0	0	0	0	0	0	0	0	0
***Total events**	**4**	100	**3**	100	**7**	100	**9**	100	**23**	100

A single 4-year under-the-average event is suggested by the reconstruction for the period 1932-1935. Subsequently, a 5-year under-the-average event is suggested by the reconstruction for the period 1974-1978 and a single 8-year under-the-average event is presented for 1905-1912. However, two 9-year under-the-average events are suggested by the reconstruction for the periods 1894-1902 and 1940-1948. The 1939-47 dry period reported by Hastenrath and Polzin (2013), is represented in the streamflow reconstruction by a one of the 9-year consecutive dry periods of the reconstruction from 1940-1948. Similarly, the 1971-78 period described by Hastenrath and Polzin (2013), is represented in our analysis in one of the 5-year periods from 1974-1978. The period 1949-2009 reports under-the-average events from one to 5-year consecutive droughts.

Likewise, the above-mean streamflow suggests that single years overwhelmingly dominate the events (62%) followed by two-year events (19%) and three-year consecutive events (4%) (Table 5.2). Similarly, the 4, 5, 6 and 10-year events are represented by single events in our reconstruction. The 4-year above-the-average event is suggested by the reconstruction for the period 1936-1939 similar to the enhanced precipitation period suggested by Hastenrath and Polzin (2013) for the 1931-1938. A 5-year above-the-average event is presented for the period 1915-1919 period. Subsequently, a 6-year above-the-average event is suggested in our study for the period 1957-1962, which closely follows a pluvial spell also reported by Herrera et al., (2017). The 10-year event is suggested for the period 1920-1929.

Table 5.2. Absolute frequency of above long-term average streamflow for August-September-October reported for the 1889-2009 period based on 30-year conglomerates.

Wet Events	1890-1919	%	1920-1949	%	1950-1979	%	1980-2009	%	Total events period 1889-2009	% of total
1 year event	2	40	2	50	6	75	6	67	16	62
2-year events	2	40	0	0	1	13	2	22	5	19
3-year events	0	0	0	0	0	0	1	11	1	4
4-year events	0	0	1	25	0	0	0	0	1	4
5-year events	1	20	0	0	0	0	0	0	1	4
6-year events	0	0	0	0	1	13	0	0	1	4
7-year events	0	0	0	0	0	0	0	0	0	0
8-year events	0	0	0	0	0	0	0	0	0	0
9-year events	0	0	0	0	0	0	0	0	0	0
10-year events	0	0	1	25	0	0	0	0	1	4
***Total events**	**5**	100	**4**	100	**8**	100	**9**	100	**26**	100

The final streamflow reconstruction for mean August-September-October streamflow is presented in figure 5.7 in m^3/s. The long-term average is highlighted in red.

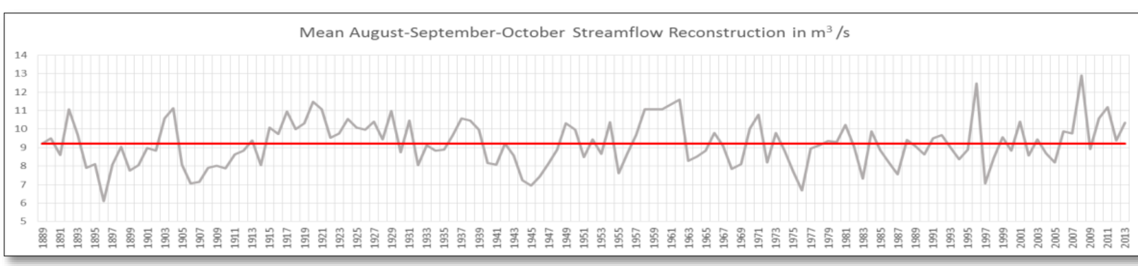

Figure 5.7. Final reconstruction for mean August-September-October streamflow at the Upper Samalá River basin in m^3/s.

Periodicity analysis and streamflow-ENSO teleconnection

The periodogram of the time series (period 1903-2013) is shown in the figure 5.8. The spectral analysis from the long time series suggest that more than 20% of the variance is explained by a 0.1 bandwidth indicating a strong decadal signal followed by a signal around a 25-year cycle that explains up almost 19% of the variance. A 3.7-year cycle is also reported in this analysis explaining around 13% of the variance. This last period could correspond to a potential ENSO bandwidths

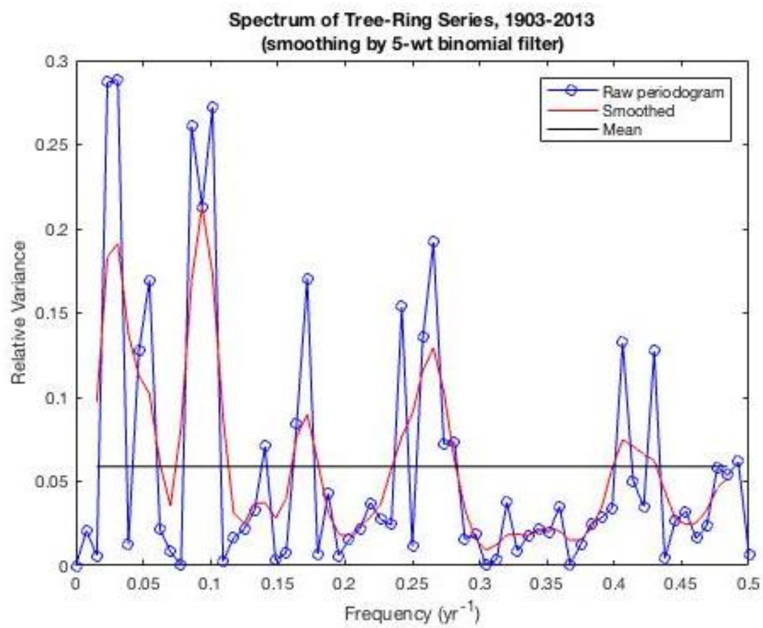

Figure 5.8. Spectral power of the chronology form *Abies guatemalensis* for the period 1903-2013

The exploration of the time series, of *A. guatemalensis* chronology to a seasonal (June-July-August) and monthly Oceanic Niño Index (ONI) at the ENSO 3.4 SST region for the period 1950-2013 yielded a negative correlation (r = -.29, p < 0.01). This correlation suggest that with incrementing temperatures in the Pacific (ENSO region 3.4) for the seasonal composite of June-July-August the mean streamflow for August-

September-October is reduced. Additionally, when comparing the reconstructed streamflow to a July-August-September ONI 3.4 index, a negative correlation $r = -0.34$ ($p < 0.01$) was found. The same exercise was performed for the August-September-October ONI 3.4 obtaining a negative correlation of $r = -0.32$ ($p < 0.01$). This results suggest a strong relationship between streamflow of the Samalá River and the seas surface temperatures in the Pacific. The future incorporation of these data to forecast the discharge at the upper Samalá River watershed can reduce the risk of communities exposed to precipitation and discharge extremes by providing timely information. Together with monitoring the volcanic activity, this could help anticipate disasters related to lahars, mud slides and floods. This information is also relevant to agriculturists because it could inform in the streamflow variability for the mid-summer drought during the evaluated period. This long record of streamflow can also inform hydroelectric producers in the mid-upper basing.

Historical events associated with streamflow variability within the Samalá River Basin.

A review of catastrophic events within the Samalá watershed was put together using information several sources (Rose 1987; UNESCO 2003; Soto et al., 2015, CONRED 2000). Altogether, the reports associated with life loss and agricultural damage (e.g. to coffee plantations) in this watershed are related to a mix of high precipitation combined with eruptions from the Santa María and Santiaguito volcanoes that generated lahars running down the hill through the hydrological channels including the Samalá River. In the most recent events, the increased precipitation and streamflow events have been intrinsically associated to the catastrophes (Soto et al., 2015).

The following map shows the coffee farms that are located within the Samalá watershed (Figure 5.9). All of them are located between 500 and 1,600 m.a.s.l.. and some of these farms (e.g. El Patrocinio), have been affected by the lahars described above. The mid-altitude basin where these farms are located represents the higher risk for lahar events (INSIVUMEH 2002).

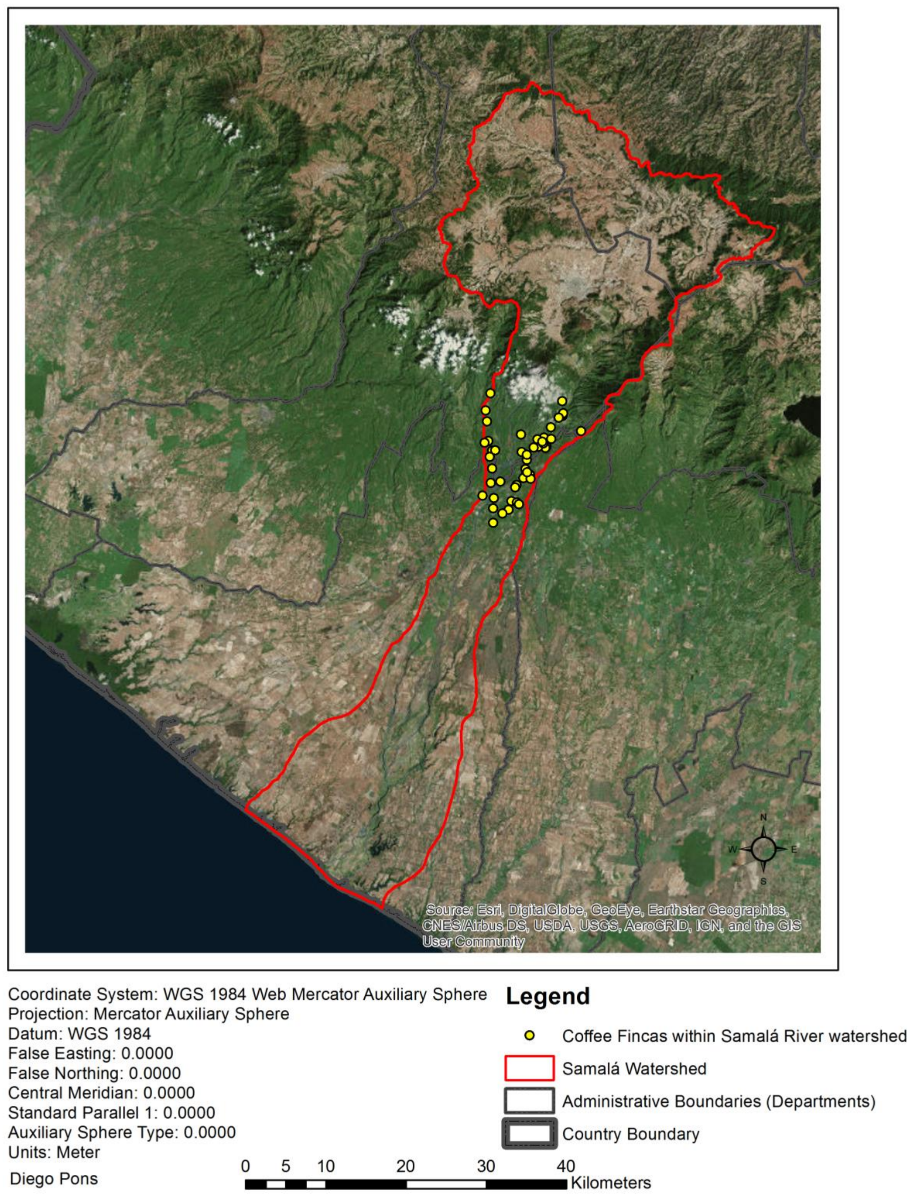

Figure 5.9. Location of 49 coffee farms within the Samalá River watershed distributed from 500 to 1600 m.a.s.l.. Source: CIAT 2012.

Our streamflow reconstruction allowed a 90-year analysis from 1902 to 1992, that suggests that out of 22 lahar events associated to activity from the Santiago volcano, 54% occurred during an above-average (9.22 m^3/s) streamflow year in our reconstruction. This suggest that after an eruption, even below-the-average streamflow can promote the mass move of mud. This could associated to soil saturation of the ridges where the mud is accumulated in previous lahar events. The impact of lahars to coffee plantations in the study area has been well documented. For instance, the lahar in 1973 completely destroyed coffee plantations in El Palmar (DesInventar 2017). A strong lahar in 1984 completely destroyed El Palmar town, an agricultural coffee producing urban settlement in Retalhuleu. In 1988 another strong lahar of mud destroyed a gas station and part of the Pan-American Highway on the 25th and 26 of August limiting the transportation in the region. Again, in 2001, a lahar was reported to damage coffee plantations.

The new long-term record also allows to evaluate the streamflow trends in a larger context of extended information. This, in turn, can inform stakeholders on the expected productivity of the hydroelectric plants located along the watershed. Also, new historical lows and highs can be derived from this reconstruction for the mean August-September-October streamflow.

Conclusions

This study presents the first streamflow reconstruction of the Upper Samalá River Basin using a tree ring-width chronology derived from the Guatemalan fir (*Abies guatemalensis*) to reconstruct mean August-September-October streamflow volumes for the period 1889-2013. Our analysis shows that strong statistical correlations are present between tree-ring width measurements and monthly natural streamflow series. The mean August-September-October streamflow variability, is dominated by single year events for both above and below the long-term mean. This reconstruction also reveals important teleconnections with El Niño Southern Oscillation that can be used to predict the mid-summer drought precipitation. Future research in this area could reveal a connection between the increased lahars reported in the area and ENSO, via increased moisture availability.

It remains necessary to assess the influence of climatic factors from previous years on both early a late wood formation, especially in relation to the soils as water reservoirs. Tree-ring measurements seem to capture a regional climate signal by means of their sensitivity to regional precipitation and streamflow and therefore are good proxies of local hydroclimate reconstructions. This new information could be incorporated into water-resource management and risk assessment plans. However, reducing the uncertainty in the early part of the chronology by adding more, longer samples remains an important task. This study is, to our knowledge, the first streamflow reconstruction in Guatemala.

CHAPTER SIX:

CORRELATION BETWEEN LOW-LATITUDE TREE GROWTH AND NDVI SATELLITE VEGETATION INDEX IN SOUTHERN GUATEMALA

Introduction

The recent increase of dendrochronological studies in tropical biomes has led to tree-ring records to become increasingly available in Mesoamerica, furthering the potential of exploration in tropical dendrochronology to fill research knowledge gaps (Stahle 1999; Tomazello et al., 2009; Wils et al., 2011; Szejner 2011; Stahle et al., 2011, 2012; Southworht et al., 2013; Anchukaitis et al., 2013, 2014). Currently, many challenges exist in tropical dendrochronology to derive accurate estimates of growth phenology, forest productivity trends and variability from tree-ring measurements (Babst et al., 2014). Some of these challenges include the lack of information regarding respiration exchange, carbon use efficiency (CUE) of tropical species, allocation of structural carbohydrates to different tissues, decay and turnover rates of tree species in tropical forests, mean residence time of the trees in the forest, and unknown biological constrains of tropical tree species (Mahi et at., 2014). In addition, there is a lack of information regarding the climate forcing behind cambial and photosynthetic activity in tropical trees due to poor and scarce climate information that limits climate sensitivity studies (Fritts et al., 2000; Dié et al., 2012; Pumijumnong and Buajan 2013; Anchukaitis et al., 2013; Mahi et al., 2014; Pons et al., 2017). Some efforts to overcome these limitations include the integration of dendrochronology data with increasingly available cutting-edge technologies such as satellite remote sensing (Kaufmann et al., 2008; Southworth et al., 2013). Until recently, these research efforts have been limited in the tropical regions by both the temporal and spatial resolution of satellite-derived imagery and the lack of chronologies outside temperate/boreal biomes (Tucker et al., 1986; D'Arrigo et al., 1987; Lopatin et al., 2006; Berner et al., 2011; Vicente-Serrano et al., 2013; Babst et al., 2014). However, with the more recent advancement of dendrochronology in tropical regions and the increase in availability of satellite derived vegetation indices, new opportunities to derive estimates of low-latitude tree growth have become available.

If combined, the use of tree ring measurements and remotely sensed Earth observations have the potential to assist in the estimation of growth phenology, forest productivity, water-use efficiency, and forest disturbances. One method to accomplish this is through the integration of tree-ring data with satellite-derived vegetation indices like the Normalized Difference Vegetation Index (NDVI), which permits assessment of cambial growth and leaf phenology (Babst et al., 2014). In turn, this information can be used to estimate regional productivity of forest systems and adjacent agricultural land productivity if the two systems share the same limiting climatic factor (e.g. precipitation) (D'Arrigo et al., (2000).

Estimating tree growth in tropical regions

Although allometric equations using radial growth and height measurements are commonly used to estimate tree growth in the tropics (Brown & Lugo 1989; Brown 1997;

Chave et al., 2005; Jenkins et al., 2003), the process of carbon allocation in tropical forests is far more complex. First, the use of energy to allocate carbon from CO2 through photosynthesis interacts with metabolic processes (e.g. respiration), known as Gross Primary Productivity (GPP), that are not accounted for in allometric equations. Secondly, the rest of the energy that does not go to respiration (e.g. structural carbohydrates), known as Net Primary Productivity (NPP), is not necessarily allocated as radial growth (Malhi et al., 2014). This complicates the notion of using only allometric equations or tree ring width measurements to estimate tree productivity.

The Normalized Difference Vegetation Index (NDVI)

Nevertheless, the potential of some satellite-derived vegetation indices, like the Normalized Difference Vegetation Index (NDVI) to estimate photosynthetic activity in plants (an indirect approximation to GPP) has been recognized as a tool with the potential to bring together the interactions between NPP and GPP to improve carbon allocation estimates, and therefore ecosystem productivity (Kaufmann et al., 2008). Satellite-derived estimates of GPP were used as early as the 1980's (D'Arrigo et al,. 1987) and have since become useful to estimate ecosystem productivity in combination with ground-based proxies of the NPP like tree-ring width (TRW) or maximum latewood density (MXD). The combination of these techniques remains an important subject of study (D'Arrigo et al., 2000; Beck et al., 2013; Mahi et al., 2014). Kaufmann et al., (2004) suggested that NDVI and TRW share a common signal that might be translated into an aggregate of NPP through the productivity of both the canopy and tree rings. D'Arrigo et al., (2000) found that, even though the dendrochronological samples represented only a small fraction of the regional vegetation, a tree-ring parameter from a single tree species has the potential to estimate the regional productivity.

Tree-ring sampling techniques and productivity assessment

The potential influence of the standard detrending methods generally used in dendrochronological studies (see Cook & Kairiukstis 1990) to estimate ecosystem productivity needs to be taken into consideration because the sampling methods can potentially introduce some bias since the collection sites are usually targeted to match the species' distribution extremes to enhance the climate signal (Beck et al., 2011). For instance, the social status of each particular individual and the method used to collect the tree-ring samples can have an impact on the estimates of total productivity of the ecosystem over a given time. No general consensus on this matter has been reported in the literature. For instance, D'Arrigo et al., (2000) recommended taking into account individuals from different social status classes, whereas Beck et al., (2011) sampled only dominant trees. An important recommendation, however, is keeping both the detrended and raw measurements of the tree rings due to the potential usefulness of the two datasets in future analysis (D'Arrigo et al., 2000; Beck et al., 2011).

Climate sensitivity assessment and NDVI estimates

Determining the intra-annual climatic factors contributing to TRW is crucial to understanding TRW-NDVI correlations, given that multiscalar, lagged relations between climate stressors and NDVI have been reported (Forbes et al., 2010 ;Vicente-Serrano et al., 2013). Kaufmann et al., (2008) suggests that NDVI series can be used to determine the timing and type of climate variables that better correlate with TRW before moving to estimate productivity. This suggestion is based on the premise that that tree rings can correlate with different values of temperature and precipitation. Kaufamann et al., (2008) also highlight the influence of light, temperature and water as climatic controls that might affect the spatial and temporal correlation between tree rings and NDVI. Given this, NDVI time series could help understand the intra-annual variation of tree rings and might help reconstruct particular months and climate factors within a year (e.g. midsummer drought and early/late wood) and this could subsequently improve the correlations to NDVI trends. The relevance of considering the influence of climate on the tree ring measurements is also critical to understand the potential of the measurements to estimate ecosystem productivity (D'Arrigo et al., 2000).

The integration of tree-ring data with remotely sensed observations is a necessary next step of research to differentiate the timing of cambial growth and leaf phenology of tropical tree species and a necessary first step to assess the potential of a single species (e.g. Abies guatemalensis) to estimate ecosystem productivity (Babst et al., 2014). The objectives of this study are: 1) to evaluate the relationship between tree-ring width measurements from Abies guatemalensis and a time series of NDVI records in a tropical forest in Guatemala, 2) to explore the intra-annual climate associations between NDVI and tree growth, 3) to explore the potential of this combined techniques as a first step to develop a continuous, annually resolved long-term estimate of ecosystem productivity and 4) to assess the interactions between climate records and NDVI in this mountainous region of Guatemala.

Methods

Study site

We focus our study within the Upper Samalá River watershed. This catchment covers 1,500 km² across the departments of Quetzaltenango, Retalhuleu and Suchitepéquez (Figure 6.1). Located between Santiaguito and Santo Tomas volcanoes, it follows the Zunil Fault Zone to the south (Bennati et al., 2011). Geologically, the area encompasses igneous and metamorphic rocks in the upper watershed and quaternary alluviums on the coastal plain. The average annual precipitation within the watershed ranges from around 2,000 mm at the top and coastal zones and displays the highest precipitation regime near the middle altitudes close to San Felipe Retalhuleu with up to 5,500 mm drawing a bimodal distribution with peaks occurring in June and September (MAGA 2001). The average annual temperature ranges from 10ºC at the highest elevation to 25.5ºC at the coastal planes (MAGA 2002). The Guatemalan fir (*Abies guatemalensis*) used here to assess the timing of correlations between Tree rings and NDVI is distributed across the high mountain range in Quetzaltenango and Sololá departments from 2700 to 3600 m.a.s.l.. These two departments are crossed by the Sierra Madre mountain range creating high elevation and temperate conditions associated with the presence of the species (González & Castañeda 1983). This complex topography creates an altitudinal gradient that gives room to a wide variety of microclimates allowing for diverse agricultural products, of which coffee is the most important.

Land cover at the study site

The ecological composition of the forest stands of *A.guatemalensis* above the agricultural region, from which the samples were collected, is relevant to this study because the reflectance perceived by satellites captures the greenness of canopy from dominant trees, but also from vegetation located in the understory (Babst et al 2010). An ecological assessment of the floristical composition of *Abies guatemalensis* forest in different forest stands of Guatemala was performed in the early 1980´s by González & Castañeda (1983). The results of such study included three different forest stands within Quetzaltenango, near the study site. Their analysis revealed three different ecological groups within the *A. guatemalensis* forests. The first group was dominated in the following order by *Pinus pseudostrobus*, *A. guatemalensis* and *P. rudis,* with some presence of *Arbutus xalapanesis*, *Litsea glaucescens*, *Prunus brachybotrya sp*. and *Quercus sp.* This ecological arrangement corresponded to María Tecún stands in Totonicapan and San Lorenzo in San Marcos *A. guatemalensis* forests. The second group was formed (in this order of dominance) by *A.guatemalensis*, *P.ayacahuite*, *Cupressus lusitanica* with a low proportion of *Arbustus xalapensis*, *Prunus brachybotrya*, *Alnus sp*. and *Quercus sp*. This ecological composite was geographically associated to Todos Santos forest stand in Huehuetenango, San Lorenzo in San Marcos and San Juan Ostuncalco in Quetzaltenango. The third ecological group was represented almost entirely by *A. guatemalensis* with a reduced proportion of *Arbutus xalapensis*, *Litsea glaucescens*, *Prunus brachybotrya* and *Quercus sp*. This stand is found exclusively in El Edén forest in Quetzaltenango. This last location is the closest site evaluated in this study to respect of our study location and resembles what the author saw during several visits to the site. This shows the complexity of *A.guatemalensis* forest stands in Guatemala regarding the vegetation composition of the stands, including those in within Quetzaltenango which should be taken into account when assessing NDVI products.

A map showing the study site is presented below (Figure 6.1). The Coffee regions are highlighted in shaded tones. The potential of assessing ecosystem productivity in the *A. guatemlensis* forest could allow the measurement of the productivity of adjacent plantations. Hence, this research is considered a necessary first step towards this goal.

Figure 6.1. Study location in southern Guatemala. The Samalá River Watershed is highlighted. Sampling location is indicated by a green star located at 14°46'39.68"N, 91°26'17.94"W at 3,300 m.a.s.l. and coffee growing areas are emphasized in gray. Source: Pons et al., 2017.

Tree ring data

I collected two to three increment core samples from 60 trees following the site, stand and tree selection described by Cook & Kairiukstis (1990) at the Kanchej forest near Quetzaltenango. A first set of samples was collected in the boreal summer of 2014 and a second one in the boreal summer of 2015. Samples were dried, mounted, and sanded. Skeleton plots were created from each sample following the cross-dating procedure described by Stokes & Smiley (1968), which allows for visual cross-dating and an initial dating for the samples. Some samples were excluded because highly growth-suppressed sections prevented measurements of ring widths (Stahle et al., 2011). The samples were measured to 0.001mm precision using a Velmex measuring table and the MJ2X software. The samples were then cross-dated and verified for adequate statistical correlations among samples and climate sensitivity using COFECHA (Holmes, 1983). After the cross-dating, I used the program ARSTAN (Cook 1985) to standardize and detrend the ring-width series using a 50 year smoothing spline to 50% amplitude of the individual series length. This detrending function was tested for each of the samples during an interactive process to verify the adequate removal of non-climatic factors in the tree series. In this study the raw, standard, and residual chronologies were used to evaluate the relationships between the different chronologies and the NDVI data set (D’Arrigo et al., 2000; Beck et al., 2011).

Climate sensitivity assessment

The instrumental data used in this study is a composite of two weather stations in the region. The precipitation data was derived from the Labor Ovalle weather station which is owned and managed by the National Weather Institute of Guatemala (INSIVUMEH), and it is located in Quetzaltenango at 14° 52.227'N, 91° 30.858'W, 12.8 km northwest of the forest stand of Kanchej (14° 46.693'N, 91° 26.192'W) at an altitude of 2,388 m.a.s.l. The precipitation record from this station begins in 1980 which was the longest, more robust record available. The temperature data was collected from the Zunil weather station located at 7.8 kilometers from the reconstruction site at 14° 45.433'N, 91° 30.067'W at an altitude of 1,880 m.a.s.l. starting in 1982. This represented 9 more years of temperature records than those available from Labor Ovalle weather station.

The precipitation dataset has no missing values. The temperature dataset from Zunil however presented a few missing values (11%) in the record that were filled using the approach suggested by Pappas et al., (2014) which suggest using an averaged value between the previous and following records (Figure 6.2).

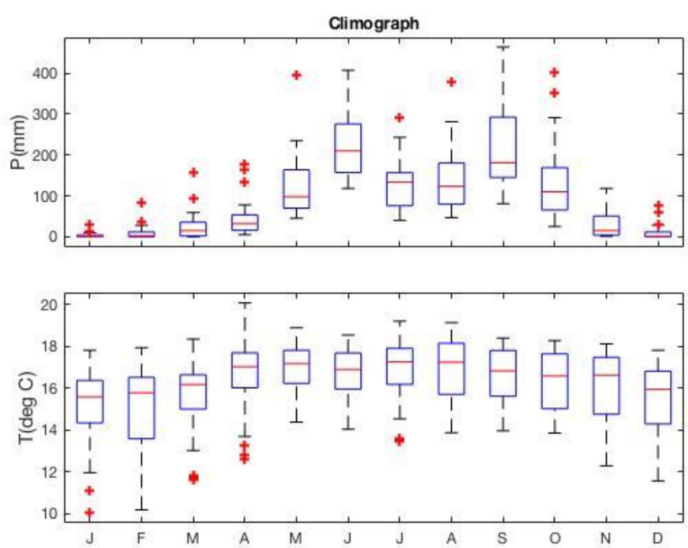

Figure 6.2. Distribution analysis of climatological records from instrumental data from Labor Ovalle (precipitation) and Zunil weather station (temperature) for the period 1982-2013 Source: INSIVUMEH 2017, INDE 2017.

I used the *seascorr* function from Matlab to assess the climate sensitivity of the chronology in monthly and seasonal composites (Meko et al., 2011). Because a lag influence between climate variables and NDVI measurements related low order autocorrelation has been described in the literature (Forbes et al., 2010; Vicente-Serrano et al., 2013), the *Abies guatemalensis* tree-ring series were assessed for climate sensitivity staring on the previous year of growth.

NDVI time series data

To derive the NDVI time series, I used several procedures. First I used the program R to download the data from the following internet address: https://ecocast.arc.nasa.gov/data/pub/gimms/. The latest version of the Global Inventory Modelling and Mapping Services (GIMMS) NDVI data termed NDVI3g (third generation GIMMS NDVI from AVHRR sensors) was downloaded using the 'gimms' package in R Studio. A series of ENVI binary files (NDVI3g.v0) containing half-monthly datasets from the timespan 1982 to 2013 were imported into R Studio and converted into Raster Layer format, or GEOTIFF. Then, the Raster Layer files containing half-monthly NDVI averages were imported into ArcMap 10.1 and the raster images were subset to the boundary of Guatemala using the Clip Tool in ModelBuilder. The model is presented in figure 6.3. A monthly NDVI composite for each month from 1982 to 2013 was generated by averaging the half-monthly datasets using the Cell Statistics tool. Monthly NDVI composite values were extracted to the geographic locations of the study area using the Extract by Mask Tool. A spreadsheet table was generated containing the Year, Month, and NDVI Values in a 13 column format and saved as a tab-separated text.

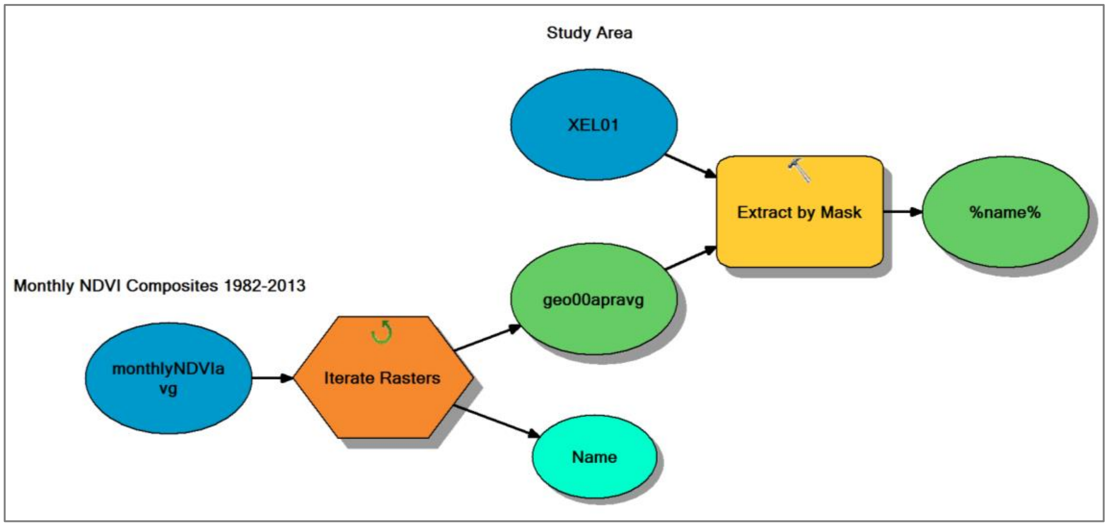

Figure 6.3. ArcMap 10.1 model used to process images from GIMMS from 1982-2013.

Tree-ring and NDVI correlation analysis

To assess potential relationships between the *Abies guatemalensis* chronologies and the NDVI series, I performed a Pearson correlation analysis using Dendroclim 2002 program (Biondi & Waikul 2004). I used the NDVI monthly averages in 13 column format and used it as input together with the raw, standard, and residual chronologies.

Results and Discussion

Tree-ring Data

The anatomic characteristics of *Abies guatemalensis* in this region are similar to those reported by Anchukaitis et al., (2013). Some samples showed local absent rings, cellular damage as well as micro-rings. Several growth-suppressed sections, usually present in the last 30 years, prevented further ring counting in most of the samples from the northwest aspect of the mountain. This has been recently reported for the same species in Guatemala (Anchukaitis et al., 2013). The reported interseries correlation and mean sensitivity of our chronology are 0.447 and 0.273 respectively (Fritts, 1976;

Holmes, 1983) which allows for the carrying out of climate analysis and reconstructions (Anchukaitis et al., 2013). The mean segment length for this subset of sample is 107 years, which could be extended in the future with more sampling. The coherence of the chronology was assessed using the Expressed Population Signal (EPS) for the standard chronology (Grissino-Mayer 2001). This is greater than 0.85 back to 1920, remains higher than 0.63 towards 1900 and finally goes down to 0.5 before 1880 probably due to sample depth. The AR-standard chronology is shown in figure 6.4 (Cook 1985).

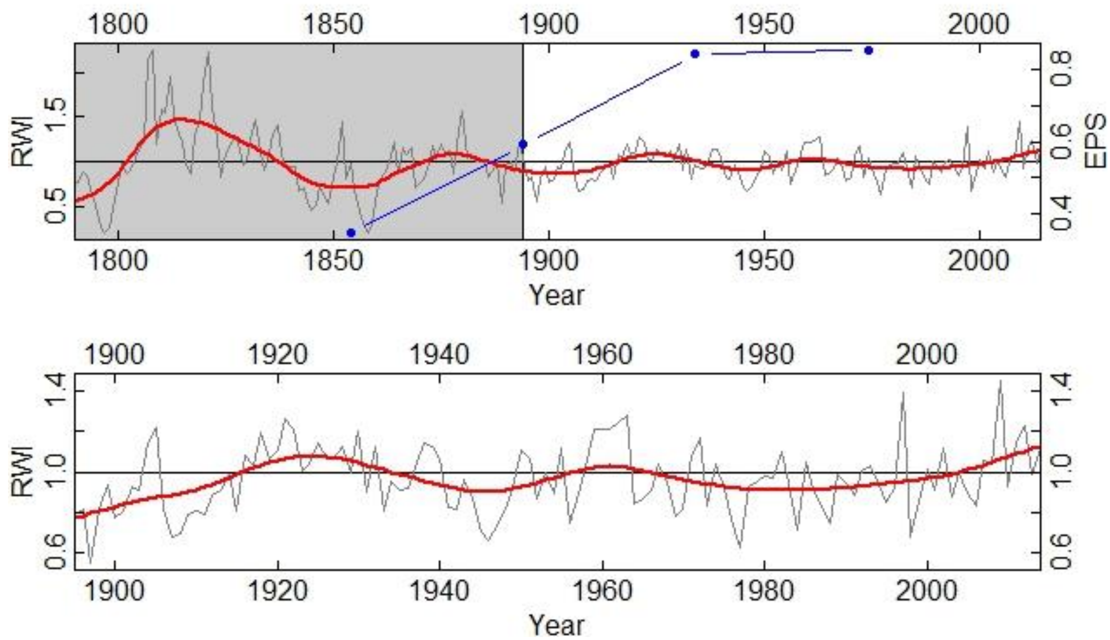

Figure 6.4 (a) Standard chronology from *Abies guatemalensis* showing EPS cut (grey) and final standard chronology

Climate sensitivity assessment

The correlation analysis performed between monthly and seasonal precipitation and temperature values from the Labor Ovalle weather station against the standard chronology using *seascorr* (Meko et al. 2011) is shown in figure 6.5. Temperature shows no significant correlation to the chronology when assessed in monthly and seasonal composites. In terms of the climate sensitivity of the chronology to precipitation using accumulated monthly values from the instrumental records available, the results from *seascorr* show a positive correlation to June and July in the individual month assessment ($p < 0.05$); July and August in the 2-month composite ($p < 0.01$ and $p < 0.05$ respectively); June, July, August, and September for the 3-month composite ($p < 0.05$, $p < 0.01$, $p < 0.01$ and $p < 0.05$) and June to September for the 4-month composite ($p < 0.05$, $p < 0.01$, $p < 0.05$ $p < 0.01$ and $p < 0.05$ respectively), all from the previous year. Also inverse correlations were found with November and December from previous year as independent months ($p < 0.01$ and $p < 0.05$ respectively).

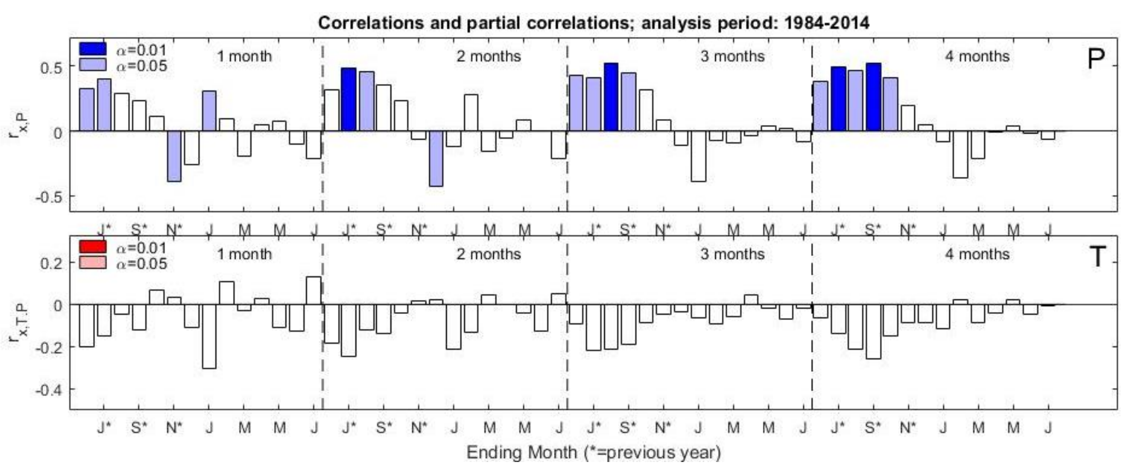

Figure 6.5. Seasonal correlations of tree-ring series against instrumental data for the period 1984-2014 using data from Labor Ovalle (precipitation), and Zunil weather station (INSIVUMEH 2017).

NDVI time series data

The resulting NDVI time series obtained from GIMMS using R package “gimms” were plotted on top of a map of Guatemala to identify the Samalá River watershed and the pixel that corresponded to the *Abies guatemalensis* forest stand (Figures 6.6 and 6.7).

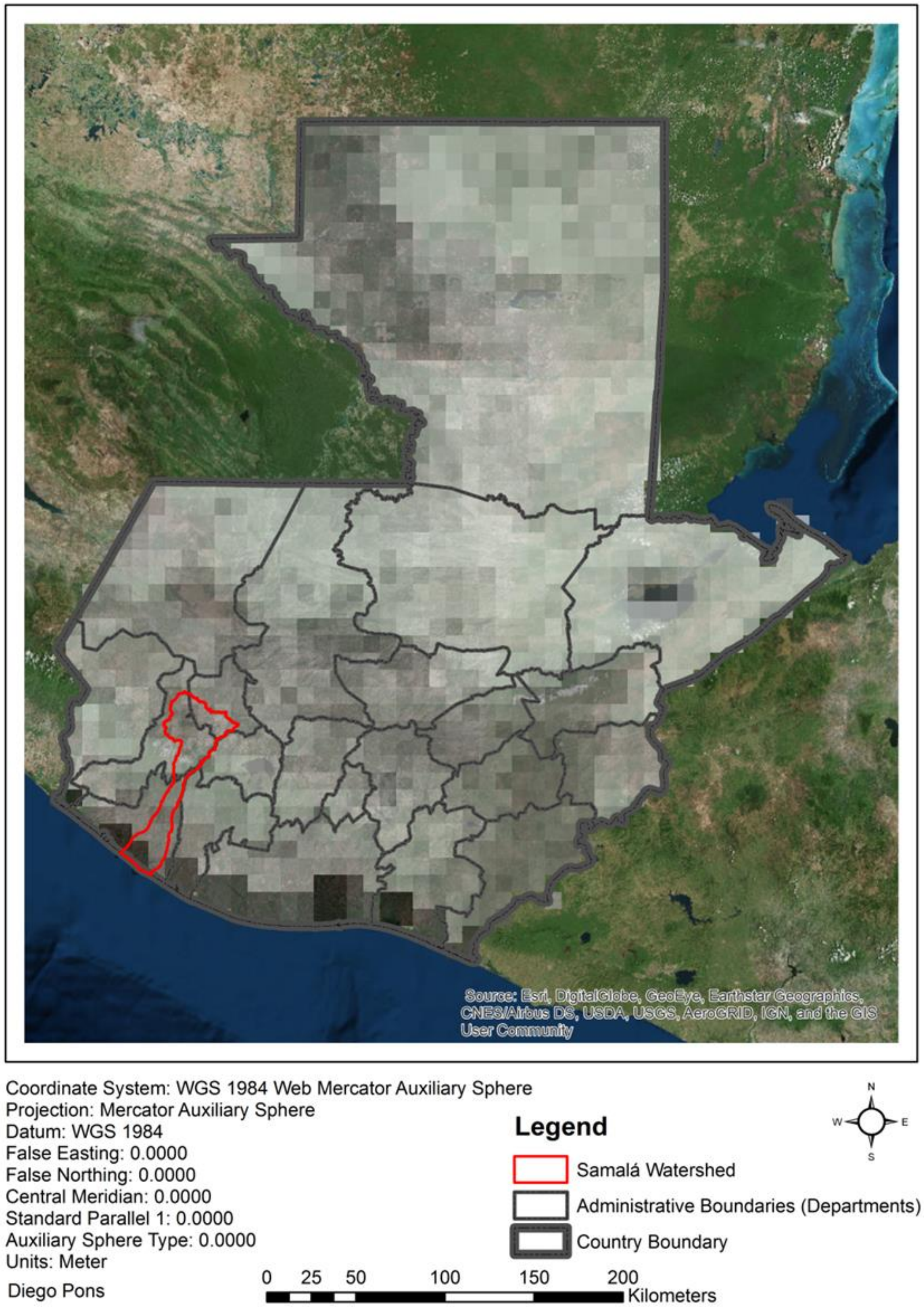

Figure 6.6. Superposition of GIMMS NDVI estimates for Guatemala. The Samalá River watershed is highlighted in red.

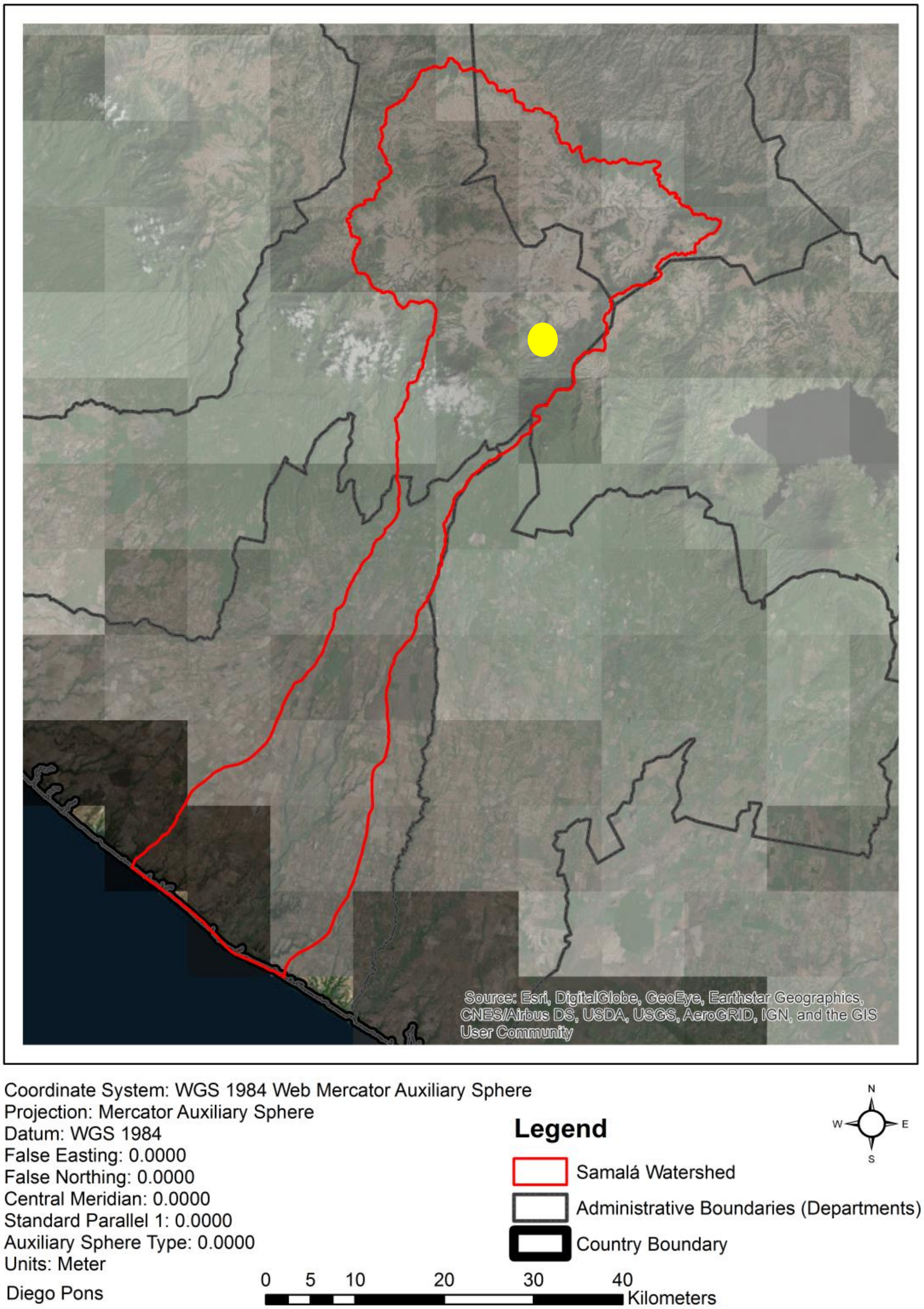

Figure 6.7. The superposition of GIMMS NDVI estimates for Guatemala. The Samalá River watershed is highlighted in red and the *Abies guatemalensis* forest stand shown as a yellow circle.

The data corresponding to the *Abies guatemalensis* forest stand pixel (including several other understory plant species described before) were plotted using a 13-column distribution following the year and monthly data from 1982 to 2013 because it is the format accepted by Dendroclim for running tree-ring measurements against climatic variables (Biondi & Waikul 2004). A graph of the NDVI time series was plotted for all the available years. The mean NDVI was calculated and plotted to highlight the behavior of the indices through the study period. The results are shown in figure 6.8.

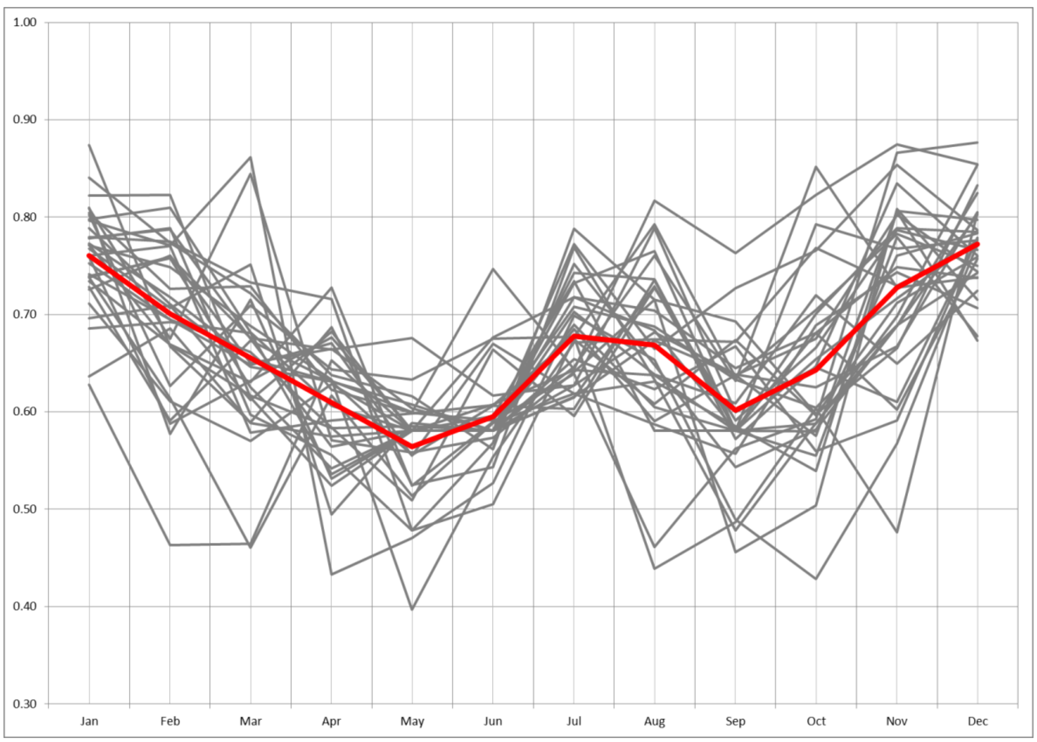

Figure 6.8. NDVI monthly averages of NDVI values for the *Abies guatemalensis* forest stand closest pixel. The annual mean NDVI value is shown as a red line.

Because the distribution of the NDVI values across the year (Figure 6.8) showed an inverse curve to that of precipitation (Figure 6.9), a regression analysis was performed to explore the correlations between NDVI and precipitation in monthly and seasonal aggregates. The results showed significant negative correlations between NDVI records and precipitation monthly records for July (r = -.30), August (r = -.40), September (r = -.30), and October (r = -.30). A seasonal aggregate of July to October NDVI and precipitation composites was evaluated, finding a significant negative correlation of -0.48 (p <0.01). Also a July –August composite yielded a significant negative correlation of r = -0.40 ($p < 0.05$).

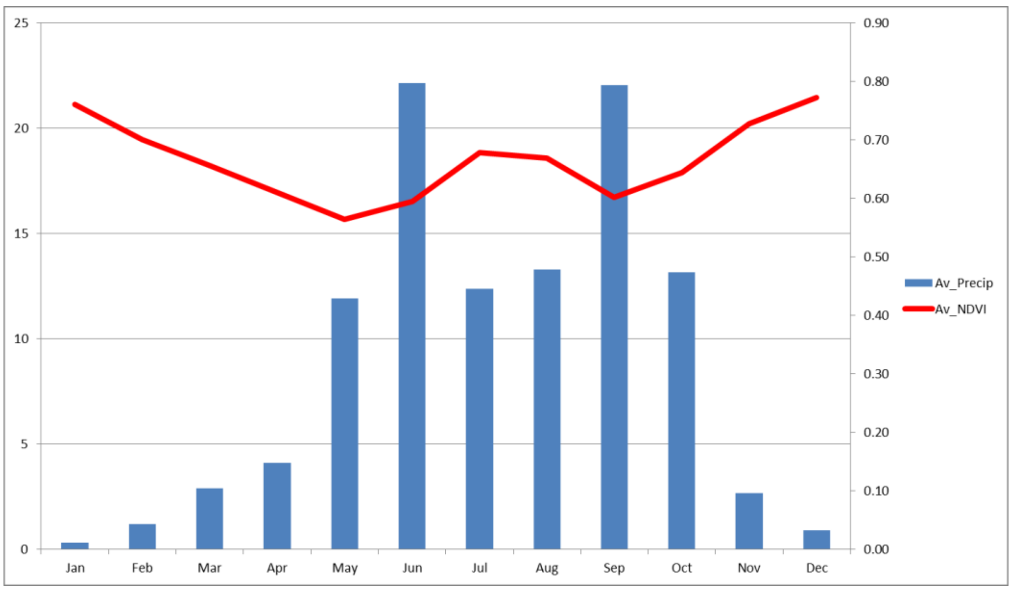

Figure 6.9. Mean monthly precipitation and NDVI indices for the period 1982-2013.

These results suggest that there is an inverse relationship between the photosynthetic activity of the vegetation within the 8 km pixel and precipitation captured at the Labor Ovalle weather station near the reconstruction site. This inverse relationship could be explained by means of the actual precipitation as a limiting factor (e.g. excess of precipitation) or by cloud cover limiting the solar radiation. This is a very important finding that suggests that the climate mechanisms behind the mid-summer drought is heavily influenced by the incoming solar radiation. This new information supports the hypothesis proposed by Magaña et al., (1999) and Rauscher et al., (2008) that suggest that higher solar radiation during the MSD increases the seas surface temperatures which allows convection to occur and generate precipitation starting in early autumn.

Tree-ring and NDVI correlation analysis

The Pearson correlation analysis performed between the raw, standard and residual chronologies yielded the following correlations; The raw chronology shows significant negative correlations to May (r = -0.37, p < 0.05), September (r = -0.40, p < 0.05), and October (r = -0.45, p < 0.05) from previous year but persistence was also captured by this chronology showing significant correlations to May (r = -0.39, p < 0.05), September (r = -0.38, p < 0.05), and October (r = -0.43, p < 0.05) from current year as well. A significant positive correlation to current January NDVI was also reported (r = 0.35, p < 0.05). The only significant correlation reported for the standard chronology is that of February of the current year (r = 0.30, p < 0.05). The residual chronology, however, shows a negative correlation to previous July (r = -0.38, p < 0.05) and a significant correlation to current February (r = 0.33, p < 0.05).

The significantly positive correlation between the tree-ring residual chronology to July-September precipitation from previous year and the significant negative correlation to winter-spring precipitation suggests that the suitable amount of precipitation in the previous year could be stored in the volcanic soils of Quetzaltenango and be used as a reservoir and made available for early wood tree growth, started by a signal from current February photosynthetic activity. The significant negative correlation of the residual chronology to previous July NDVI index suggests that an increment in photosynthetic activity via less cloud and/or less precipitation during the mid-summer drought has an influence on the radial growth by reducing the amount of water that the soils could accumulate to start or sustain the growth from the following year. Similarly, the evidence suggests that any addition of water to the soil reservoir will have a negative impact in radial growth probably due to a saturation of the water table that is not suitable for *A. guatemalensis.*

At high latitudes, both the canopy and radial growth are largely dependent on temperature, substrate and tree water balance (Fritts et al., 2000). In this location, however, precipitation seems to have an important influence on determining both the leaf and radial growth.

Conclusions

Our analysis suggests that the NDVI records from this location are inversely correlated to precipitation in the Upper Samalá River watershed at the location of the *A. guatemalensis* forest stand Kanchej. The most important finding, however, is related to the inverse relationship between a reduced NDVI (an indirect measurement of photosynthetic activity) during the two peaks of the bimodal distribution of precipitation and the resume of photosynthetic activity (NDVI) during the mid-summer drought. This supports the hypothesis that solar input promotes the convection that generates clouds for the following precipitation peak during September-October. Yet, more weather stations need to be compared for a regional assessment.

The results from the different relationships between independent analyses of precipitation and NDVI sensitivity of *A. guatemalensis* and the correlation between precipitation and NDVI itself suggest that precipitation is a modulator of radial growth of *A. guatemalensis* in this location of Guatemala. It highlights the low order autocorrelation of the species in this location and supports the findings of an influence from previous year precipitation. These findings can be used to refine the knowledge on the climatic controls on *A. guatemalensis* ring-width. It also identifies some of the active photosynthetic periods of *A. guatemalensis* and sets the route to move towards the estimation of ecosystem-level productivity and the estimation of inter-annual changes in terrestrial vegetation.

Climate driven changes on ecosystem productivity in Guatemala are neglected in projections of future carbon storage in mitigation plans. The information generated here could help understand more realistically the variability in carbon uptake in tropical forest to be included in mitigation management strategies like the REDD + project. The net solar radiation during the mid-summer drought seems to support the hypothesis that convection during these months has an influence on the second period of rainfall in the region. In addition, this study represents to the best of our knowledge, the only study assessing the relationships between NDVI and tree-rings in Guatemala.

CHAPTER SEVEN

SUMMARY

The main objective of this dissertation has been to expand the tree-ring network in Guatemala and generate long-term climate information that could then be used by agriculturalist in Guatemala. Overall, these objectives have been satisfied and long-term climate hydrological records have been created. This research has demonstrated successful cross-dating and climate sensitivity of *Abies guatemalensis* in the Pacific slope of Guatemala. The research has also produced a 124-year record of precipitation from mean June-July-August, linked to the mid-summer drought in relevant in Guatemala for agriculture. The study also suggests that temperature has little influence on determining the radial growth of the species in this region. The precipitation from previous June-October seems to have an influence on early wood formation of *A, guatemalensis* in this location. This hypothesis needs further research and was not assessed during this study. The precipitation from June-July-August at the reconstruction site seems to receive an important influence from SST in the Pacific Ocean in the form of ENSO in the region 3.4. The inverse relationships between May, June and July ONI index to the mean precipitation in June-July-August could be used as an early warning system by agriculturalist in the region to assess the potential precipitation expected during the mid-summer drought. The absolute frequency analysis suggests that single year droughts dominate the record. Equally important in this region are the pluvial because precipitation extremes in the form of excessive rainfall have had an impact on agriculture, infrastructure and the overall quality of life of the residents within the Samalá River watershed. To this respect, the single year above-the-average events also dominate the evaluated period. The relationships between four or more consecutive above-the-mean precipitation years and coffee diseases could inform farmers on potential outbreaks similar to the ones examined here (e.g. *Fumagina sp*, *Ceratocystis fimbriata*, and *Mycena citricolor*) or other moisture-related diseases. Overall, the frequency of precipitation events reconstructed here could be useful for stakeholders (including agriculturalist and hydropower production managers) in the region regarding adaptation strategies to future precipitation variability.

This study also presents a streamflow reconstruction of the Upper Samalá River watershed using a tree ring-width chronology derived from the Guatemalan fir (*Abies guatemalensis*) to reconstruct mean August-September-October streamflow volumes for the period 1889-2013. Our analysis shows that strong statistical correlations are present between tree-ring width measurements and monthly natural streamflow series. The mean August-September-October streamflow variability is dominated by single year events for both above and below the long-term mean streamflow. This reconstruction also reveals important teleconnections with SST at the 3.4 ENSO region that can be used to predict the streamflow for these months and allows long-term trend studies. This study is, to our knowledge, the first streamflow reconstruction in Guatemala.

Our analysis suggests that the NDVI records are inversely correlated to precipitation in the Upper Samalá River watershed at the location of the *A. guatemalensis* forest stand Kanchej. The results from the different relationships between the independent analyses of precipitation and NDVI sensitivity of *A. guatemalensis* and the correlation between precipitation and NDVI suggest that precipitation is a modulator of radial growth of *A. guatemalensis* in this location of Guatemala. These findings can be used to refine the knowledge on the climatic controls on *A. guatemalensis* ring-width. It also identifies some of the active photosynthetic periods of *A. guatemalensis* and sets the route to move towards the estimation of ecosystem-level productivity and the estimation of inter-annual changes in terrestrial vegetation. Climate driven changes on ecosystem productivity in Guatemala are neglected in projections of future carbon storage in mitigation plans. The information generated here could help understand more realistically the variability of carbon uptake in tropical forest to be included in mitigation management strategies. In addition, this study represents, to the best of our knowledge, the only study assessing the relationships between NDVI and tree-rings in Guatemala. This new information could be incorporated into water-resources management and risk assessment plans. Finally, the most important finding of this study is the evidence supporting the hypothesis that solar radiation during the mid-summer drought can be responsible for the convection processes that create clouds and precipitation for the early autumn represented by the second precipitation peak for Guatemala. This new evidence sheds light on the mechanisms that modulate the precipitation in the region and could help the understanding of potential changes generated by anthropogenic global warming forcing on these systems. Adding more, longer samples remains an important task.

Regarding the usefulness of this information to stakeholders, the early involvement of community leaders, municipal forest trainees, national and international students, and coffee farmers in this study has led to a better receptiveness of the results in relevant circles of decision makers (e.g. coffee farmer and the National Coffee Association , ANACAFE). Yet, the challenge to communicate and make the information comprehensive to coffee farmers remains a complex issue. This is a common problem identified in actionable science literature (Tarhule & Lamb 2003; Sivakumar 2006; Brondizio & Moran 2008; Lynch et al., 2008; Gunakusera 2010; Beier et al., 2016; Pons et al., 2017). The gap between climate science and its transformation into relevant climate information deters agriculturalists from implementing actions and policy makers from developing policies to help smallholder farmers adapt to climate change in Guatemala (Donatti et al., 2017; Pons et al., 2017). Newly generated climate information needs to be peer-reviewed and validated. This important and basic step of the scientific research becomes even more relevant when the science being created (e.g. the expansion of dendrochronology in the tropics) is exploratory and when its full potential, limitations, and usefulness need to pass rigorous scientific scrutiny. Although inalienable from science, this slow peer-reviewed process that usually ends with publications in English sitting in digital libraries, contrast with the urgency for climate information in the world´s most biodiverse and yet most vulnerable regions of the world to climate variability and climate extremes (Moser 2010; Klenk et al., 2015). Not only this reflects a North-South divide in climate change research but it has a direct impact on least developed countries vulnerable to climate change and how they manage risk (Blicharska et al., 2017).

Furthermore, after passing this processes the problem of scientific products sitting in the peer reviewed literature after exhaustive inspection under the loading dock approach suggested by Cash et al., (2006), is that it needs to overcome several other barriers that are usually case specific and dynamic and that keep this information from generating adaptation strategies and actions (Pons et al., 2017). For instance, a document containing climate information for Guatemala might seem "available" in peer-reviewed literature, but several language, internet access and even scholarship of some stakeholders limit access to this "raw" climate information for the majority of Guatemalans.

For instance, the *additional* step of outreach or science communication described by Beier et al., (2016) under the loading dock approach proposed by Cash et al., (2006), should not be considered *additional* but mandatory instead. During the early stages of our study, the involvement of community leaders and school teachers to communicate preliminary findings (e.g. successful identification of annually resolved rings) during the development of it was well received, appreciated and enabled future visits to the study site (Figures 6 & 7, Appendix C). Because the process of generating new climate information in this site using dendrochronology took several years, a constant communication with coffee farmers and ANACAFE technicians allowed for a preliminary validation of the usefulness of results and sometimes it led to a re-orientation of the best way to communicate the findings to make the information comprehensive. This continuous communication and participation in coffee and climate workshops and meetings in Guatemala also allowed me to get feedback regarding the level of climate knowledge within coffee farmers.

In order to communicate the preliminary results of the study and to validate the reconstructed climate records and their impacts to local coffee farmers within the Samalá River watershed, a meeting with ANACAFE board of directors was organized (Figure 10, Appendix C). Future workshops with stakeholders in Guatemala are planned for validation and the sharing of the results of this investigation.

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APPENDIX A

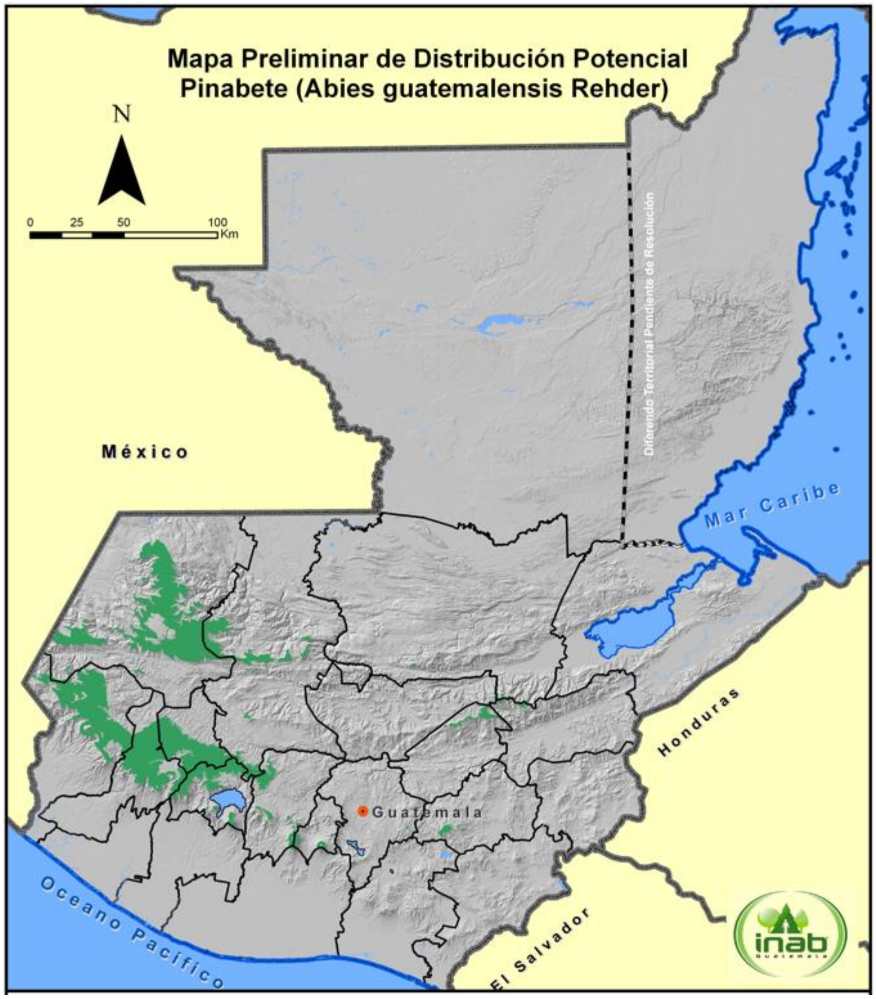

Figure 1. Official preliminar distribution of *A.guatemalensis* in Guatemala. Source: INAB

Funding

This research was enabled with funding from National Science Foundation grants BCS 1263609 and 0852652, National Geographic, Conference of Latin Americanist Geographers, and Latin American Specialty Group and Latin American Specialty Group Field Study Awards, and the Lawrence Herold Fund at the University of Denver.

APPENDIX B

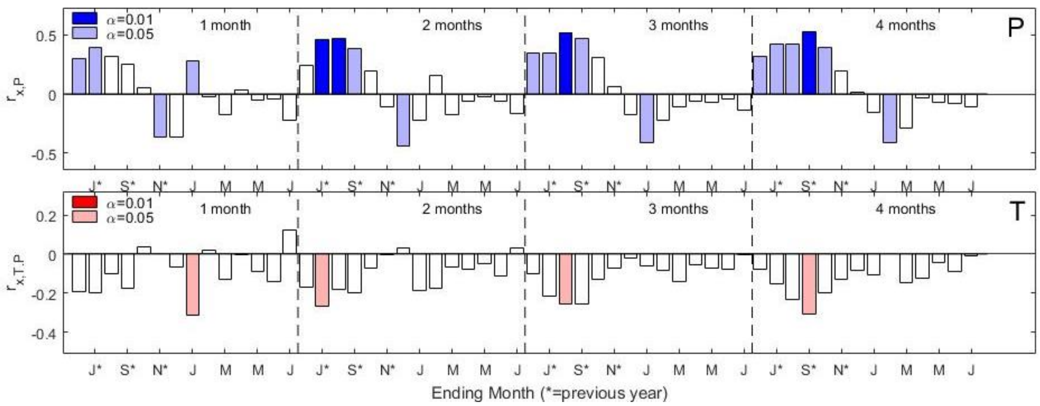

Figure 2. Monthly and seasonal correlations of tree-ring series against instrumental data for the period 1984-2014 using data from Labor Ovalle (precipitation) and Zunil weather station (temperature).

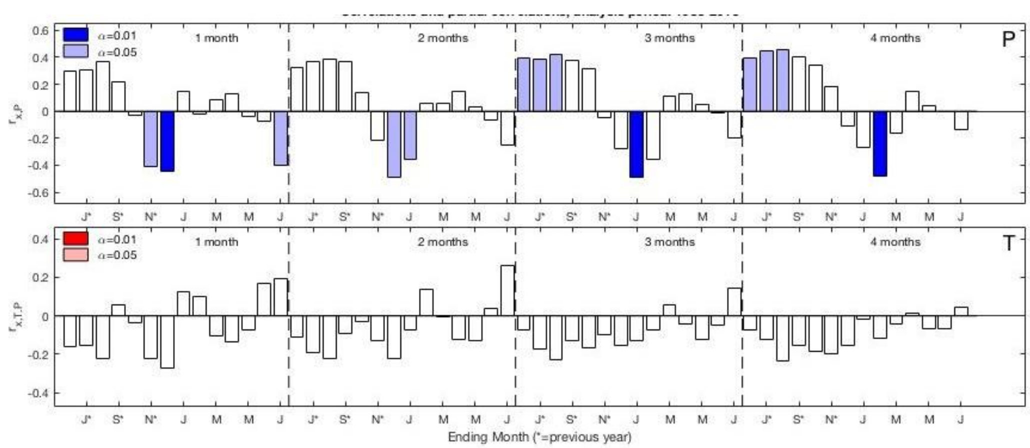

Figure 3. Monthly and seasonal correlations of tree-ring series against gridded GPCC v7 at 1.0° and CRU TS 3.34.01 data for the period 1983-2013.

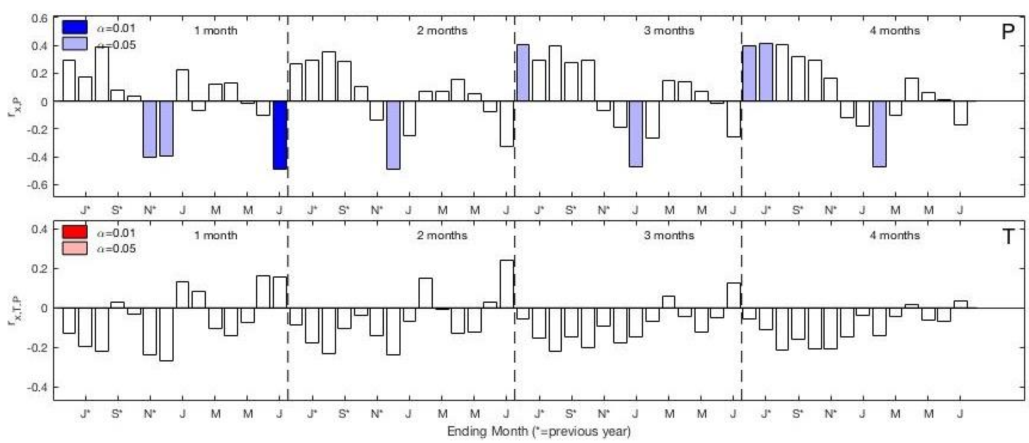

Figure 4. Monthly and seasonal correlations of tree-ring series against gridded GPCC v7 at 0.5°and CRU TS 3.34.01 data for the period 1983-2013.

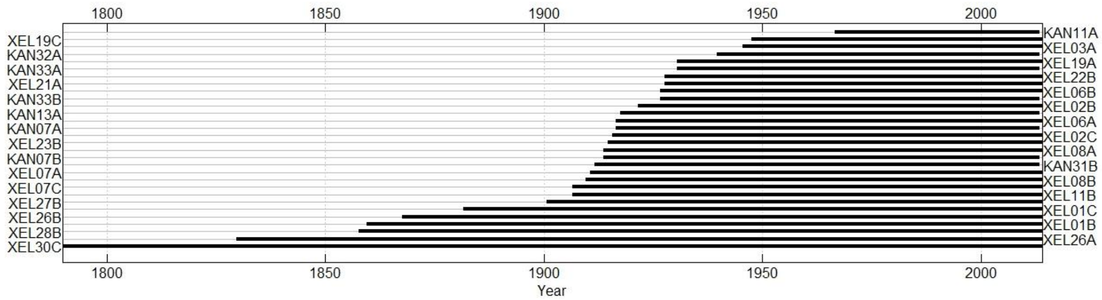

Figure 5. Time coverage by individual tree radii from *A. guatemalensis*.

APPENDIX C

Figure 6. Sharing preliminary results with community leader Don Ramón and teachers from the local school at Cantel, near our reconstruction site.

Figure 7 .The author showing the formation of tree rings and the logic behind the reconstruction to community leader Don Ramón and teachers from the local school at Cantel, near our reconstruction site.

Figure 8. Fieldtrip in Kanchej forest, teaching a municipality forest trainee on the use of increment borers for dendrochronology studies.

Figure 9. Fieldtrip in Kanchej forest, teaching a municipality forest trainee on the sampling methods used in dendrochronology studies.

Figure 10. ANACAFE headquarters. Meeting with Board of Directors in ANACAFE to present preliminary results.