

Spring 5-18-2011

ASSESSING SEASONAL FEATURES OF TROPICAL FORESTS USING REMOTE SENSING

Roberto Bonifaz-Alfonzo

University of Nebraska-Lincoln, sarnoso@msn.com

Follow this and additional works at: <http://digitalcommons.unl.edu/geographythesis>



Part of the [Environmental Monitoring Commons](#), [Geographic Information Sciences Commons](#), [Natural Resources and Conservation Commons](#), [Other Earth Sciences Commons](#), and the [Physical and Environmental Geography Commons](#)

Bonifaz-Alfonzo, Roberto, "ASSESSING SEASONAL FEATURES OF TROPICAL FORESTS USING REMOTE SENSING" (2011). *Theses and Dissertations in Geography*. 11.
<http://digitalcommons.unl.edu/geographythesis/11>

This Article is brought to you for free and open access by the Geography Program (SNR) at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Theses and Dissertations in Geography by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

**ASSESSING SEASONAL FEATURES OF TROPICAL FORESTS USING
REMOTE SENSING**

by

Roberto Bonifaz-Alfonzo

A DISSERTATION

Presented to the Faculty of
The Graduate College at the University of Nebraska
In Partial Fulfillment of Requirements
For the Degree of Doctor of Philosophy

Major: Geography

Under the Supervision of Professor James W. Merchant

Lincoln, Nebraska

April, 2011

ASSESSING SEASONAL FEATURES OF TROPICAL FORESTS USING REMOTE SENSING

Roberto Bonifaz-Alfonzo Ph.D.

University of Nebraska, 2011

Advisor: James W. Merchant

Tropical forests are key components of the biogeochemical cycles, complex in structure, diversity and dynamics, also, tropical regions have been deforested and modified by human activities particularly for agriculture. Understanding the inter-annual and intra-annual variation dynamics of tropical regions could give valuable information on temporal characteristics of ecosystems behavior which is important for mapping and monitoring. This dissertation assesses seasonal and inter-annual changes in the tropical land cover that may be related to changes in the natural environment and/or human activities. Research was focused on the Mayan forest located in southern Mexico and Northwest Guatemala, one of the northern-most important tropical areas in the continent. Using vegetation index products from the Moderate Resolution Imaging Spectroradiometer (MODIS) from 2001 to 2005, the vegetation condition “greenness” was modeled through temporal profiles. The higher spatial resolution data and the availability of two vegetation indices: the standard Normalized Difference Vegetation Index (NDVI), and the Enhanced Vegetation Index (EVI), designed to improve sensitivity to differences in vegetation from sparse to dense vegetation conditions, offer a great opportunity to model vegetation dynamics in tropical areas. Additionally, the Wide Dynamic Range Vegetation Index (WDRVI) which is derived from the NDVI and designed to enhance the spectral response where the NDVI

saturates, is included. Comparison between the different vegetation indices is analyzed by means of cross-plots and a wavelet analysis. Then a Fourier series approximation calculation was applied to extract the main seasonal components (high harmonics amplitude and phase) of the biweekly greenness profiles in order to input to an unsupervised classification to obtain a land use/land cover map and to compare mean amplitude and phase parameters value between years.

Results show differences between indices in terms of seasonal and vegetation response. In terms of mapping the WDRVI was the index with better performance. Fourier parameters mapping, particularly the first harmonic phase, was sensitive to annual variation of environmental conditions (precipitation). The use of multitemporal observations through remote sensing observations, provide a continuous and dynamic view of tropical regions to support monitoring and sustainable development and management of environmental policies.

Acknowledgements

This work is dedicated to my mother Florecita and to the memory of my father Roberto.

I would like to thank my academic advisor, James Merchant, for giving his support during this hard and long process to finish my PhD. My sincere gratitude to my doctoral committee: Dr. Donald Runquist, Dr. Brian Wardlow and specially to Dr. Anatoly Gitelson for their invaluable academic support and comments during my doctoral research. I want to acknowledge Dr. Steve Lavin who was a member of my committee at the beginning and Dr. Drew Tyre for his help with the Fourier methods in the early stage of my work. My fellow friends and colleagues at CALMIT, all helped me also during this process. I would like to mention: Kirsten, Giorgio, Patti,, Andrés, Veronica, Deepak, Rick, Jared, Brian, Milda and Kenny, also to Bernice and Joyce. Special thanks to Naikoa and his lovely wife Adela for their friendship. Roman Alvarez my local advisor for his invaluable support continuous advice and friendship. To Ana Lillian Martin, who reviewed parts of the manuscript in several occasions and Victor Velasco who helped me with the wavelet analysis and other valuable comments. Thanks to Mauro Valdes for his unconditional and unwavering friendship.

My affection to my aunt Chabe, my sisters Maryross, Cecy, and specially Lety for her support and help in many ways. My gratitude to my wife Dely (I will love you forever), my sons Alejandro and Matias (you will be always my kids), and finally to my son Roberto a little person who apparently suddenly appears in my life and with a smile captures my heart.

This research was sponsored by the Academic Support Program from the Dirección General de Asuntos del Personal Académico (DGAPA) of the Universidad Nacional Autónoma de México.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	IV
CHAPTER 1 INTRODUCTION.....	1
1.1 Introduction.....	1
1.2 Background.....	4
1.3 Research Objectives.....	10
1.4 Study Area	11
1.5 Synopsis of Methods	13
1.6 Implications of Research	15
1.7 Organization of the Dissertation	16
References.....	17
CHAPTER 2 BACKGROUND.....	23
2.1 Introduction.....	23
2.1.1 Climate in the Tropics	23
2.1.2 Carbon cycling in tropical forests	25
2.1.3 Forest Degradation and Forest Fragmentation	26
2.1.4 Succession	27
2.2 Multitemporal Remote Sensing.....	30

2.3 Remote Sensing Phenology	31
2.3.1 Phenological Variables.....	32
2.3.2 Annual Response of Humid and Sub-humid Tropical Vegetation	34
2.3.3 Applying Remote Sensing Phenology to the Tropics.....	37
References	40

CHAPTER 3 STUDY AREA..... 48

3.1 The Neotropical Region.....	48
3.2 Occupation History	50
3.3 Study Area Location	51
3.4 Topographic Regions.....	52
3.5 Climatic Characteristics	56
3.6 Land cover/Land use	60
3.7 Protected Areas and the Mesoamerican Biological Corridor	62
References	65

CHAPTER 4 DATA AND METHODS..... 68

4.1 Data Sources	68
4.2 Data Preprocessing	70
4.3 Vegetation Indices.....	72

4.4	Multitemporal Maximum Vegetation Indices Composites	74
4.5	Analysis Procedures.....	76
4.5.1	Indices Comparison.....	76
4.5.2	Modeling Land cover Seasonality of Tropical Regions	77
	References	87

CHAPTER 5 RESULTS..... 91

5.1	Comparison of Vegetation Indices	92
5.2	Fourier Series Analysis Results	117
5.2.1	Amplitude and Phase Angle Parameters	118
5.2.2	Per-pixel Analysis	128
5.2.2.1	Mean Conditions (a_0 Fourier parameter)	129
5.2.2.2	Amplitude and Phase.....	134
5.2.3	Land cover/Land use Classification	149
5.2.3.1	Accuracy Assessment.....	155
	References	161

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH 163

6.1	Summary.....	163
6.1.1	Vegetation Indices Comparison	163
6.1.2	Fourier Parameters Meaning	164
6.2	Recommendations for Future Research.....	167

LIST OF FIGURES

Figure 1. Eight biogeographic realms and fourteen biomes according to Terrestrial Ecoregions of the World: a New Map of Earth (Olson et al. 2001).....	2
Figure 2. Tropical forests (shown in dark green color) The occurrence between the tropic of Cancer and tropic of Capricorn. Source: http://earthobservatory.nasa.gov/Features/Deforestation/	2
Figure 3. Phenological transition points and phases. (modified from: Zhang, et al. 2001)	6
Figure 4. Multi-year raw (non-smoothed) vegetation index profile showing strong seasonality (tropical deciduous forest site) over a five year period starting within January. Greenness increases as the vegetation index approaches a value of 1. In general, peaks coincide with wetter and warmer periods and valleys with dry periods.....	7
Figure 5. Typical multi-year raw (not smoothed) vegetation index profile showing little seasonality (tropical rain forest site) over a five year period starting with January. Greenness increases as the vegetation index approaches a value of 1. The general trend shows no variation. Local variations may be related to cloud contamination of the imagery. The profile includes five years starting with January.	8
Figure 6. Study area: The red square portrays the extent of the study area covering southeastern Mexico-northern Guatemala. The image is a shaded relief map showing in green shades the major natural protected areas.....	12

- Figure 7. Temperature and precipitation historical monthly averages (Boca del Cerro weather station in southeastern Mexico close to the Guatemala Border). High mean temperatures typical from tropical regions. Precipitation regimen show higher values during the summer months and a local minima between the months of June and September. 24**
- Figure 8. Single year tropical rain forest sample. Values of the NDVI are very high and show almost no variations throughout the year..... 36**
- Figure 9. Single year, tropical deciduous forest sample. The NDVI values increase from the dry months to the wet months..... 37**
- Figure10. The red square represents the extent of the study area plotted over a 16 day free cloud composite MODIS image. The inset show the location of the study area in North America 52**
- Figure 11. Elevation and Geomorphic Units of the study area. This map shows the complexity of the topography of the study area which influences the environmental condition..... 55**
- Figure 12. Broad climatic zones used in this work. Green triangles represent the meteorological stations. Temperate and sub-humid conditions are strongly influenced by the topography. 57**
- Figure 13. Tropical humid climograph (Boca del Cerro weather station). High mean temperatures uniformly distributed. High precipitation is more abundant during the summer..... 58**
- Figure 14. Tropical sub-humid climograph (Aquespala weather station). Located in an area surrounded by mountains which modifies the precipitation regime**

(strong dry/wet seasons) whereas the high temperatures are maintained throughout the year.	59
Figure15. Temperate conditions climograph. San Cristobal weather station. In temperate tropical regions the temperature is strongly modified by elevation resulting in lower values. The precipitation regime shows dry/wet conditions with the local minima values during the months of June and August.	60
Figure 16. Land use/ Land cover map showing the main classes. (Source: National Forest Inventory from Mexico and Conservation International data for Central America, circa 2000).	61
Figure 17. Natural protected areas. Protected areas are located in different environment conditions including tropical forests, cloud forests and wetlands among others.	64
Figure 18. MODIS 16 day NDVI cloud free tile h09v07 which covers the study area in ISIN original projection. Darker tones represent less vegetation whereas whiter tones more abundant vegetation.....	71
Figure 19. MODIS 16 day NDVI cloud free tile h09v07 which covers the study. Reprojected to a Lambert conical conformal projection. Darker tones represent less vegetation whereas whiter tones more abundant vegetation.....	71
Figure 20. Sine functions for one, two and three periods. As the number of periods increase more complete cycles are for the same period of time.....	79
Figure 21. Sum of three sine functions. As time increases, the added function effect is less important.....	80

- Figure 22 Fourier series approximations fitting (one and two cycles). The first period or cycle defines the overall shape of the original function, the two period case adjust with more detail to the original data. 81**
- Figure 23. Fourier series approximation fitting (four and six cycles). As the number of periods is increased the adjustment to the original function is closer. 81**
- Figure 24. Comparison between the data, the estimated values and harmonics decomposition (Tropical Deciduous Forest site). Due to the nature of the data (strong dry/wet conditions) the first harmonic is high. As the number of harmonics increase the resulting functions are flatter and flatter showing local variations of the data. 84**
- Figure 25. Comparison between the data, the estimated values and harmonic decomposition (tropical rainforest site). Since the data shows no seasonal behavior, the resulting functions are flatter compared with the tropical deciduous forest case. Lower harmonics shows local variations of the data. 84**
- Figure 26 NDVI, EVI and WDRVI comparison over five years for tropical deciduous forest..... 93**
- Figure 27. 2001 index comparison for a tropical deciduous forest site. The EVI and NIR-Red show more local variation in time and VI value whereas the other two indices have a similar pattern. 94**
- Figure 28. 2002 index comparison for a tropical deciduous forest site. The EVI and NIR-Red show more local variation in time and VI value whereas the other two indices have a similar pattern. 95**

Figure 29 2003 index comparison for a tropical deciduous forest site. The EVI and NIR-Red show more local variation in time and VI value whereas the other two indices have a similar pattern.	95
Figure 30. 2004 index comparison for a tropical deciduous forest site. The EVI and NIR-Red show more local variation in time and VI value whereas the other two indices have a similar pattern.	96
Figure 31. 2005 index comparison for a tropical deciduous forest site. The EVI and NIR-Red show more local variation in time and VI value whereas the other two indices have a similar pattern.	96
Figure 32. Five year data for tropical rain forest. The EVI shows a seasonal behavior (annual increase and decrease of the value). Index values look very noisy.....	98
Figure 33. Five year smoothed data for tropical rain forest. The EVI shows a seasonal behavior (annual increase and decrease of the value).....	99
Figure 34. 2001 Index comparison for a tropical rainforest site. The EVI shows a seasonal pattern similar to the precipitation regimen whereas the other two indices show the opposite.	100
Figure 35. 2002 Index comparison for a tropical rainforest site. The EVI shows a seasonal pattern similar to the precipitation regimen. The other two indices in this year, also approach the seasonal pattern but still have noisy data.	100
Figure 36. 2003 Index comparison for a tropical rainforest site. The EVI shows a seasonal pattern similar to the precipitation regimen. The other two indices in this year, also approach the seasonal pattern but still have noisy data.	101

Figure 37. 2004 Index comparison for a tropical rainforest site. The EVI shows a seasonal pattern similar to the precipitation regimen. The other two indices in this year, also approach the seasonal pattern but still have noisy data.	101
Figure 38. 2005 Index comparison for a tropical rainforest site. The EVI shows a seasonal pattern similar to the precipitation regimen. The other two indices in this year, also approach the seasonal pattern but still have noisy data.	102
Figure 39. NDVI versus EVI relationship. The trend line and R^2 value is for the tropical deciduous forest.	104
Figure 40. NDVI versus WDRVI relationship (notice the non-linear relationship between them).....	104
Figure 41. EVI versus WDRVI relationship.....	105
Figure 42. NIR-Red vs vegetation indices. Tropical deciduous forest case.	106
Figure 43. NIR-Red vs vegetation indices. Tropical rainforest case.	106
Figure 44. Tropical deciduous forest NDVI wavelet spectrum. The graph shows a strong annual period (value of 1).....	108
Figure 45. Five year, tropical deciduous forest EVI wavelet spectrum. The graph shows a strong annual period (value of 1). Also local variations of less periods of time are detected (closed isolines less than a period of 0.25)	108
Figure 46. Five year, tropical deciduous forest WDRVI wavelet spectrum. The graph shows a strong annual period (value of 1) similar to the NDVI case. ...	109
Figure 47. Five year, tropical rainforest non-smoothed NDVI wavelet spectrum. The maximum period is in 0.25 of a year, followed by the annual (Period = 1).	111

- Figure 48. Five year, tropical rainforest non-smoothed EVI wavelet spectrum. In contrast with the other VI's in this case, annual period is clearly marked. 111**
- Figure 49. Five year, tropical rainforest non-smoothed WDRVI wavelet spectrum. The period of 1 (annual) is more clearly shown than the NDVI but less than the EVI and it is stronger during the first two years. It is still an important period of 0.25 of year probably related to noise and spurious data. 112**
- Figure 50. Tropical rainforest NDVI (smoothed) wavelet spectrum. Compared with the non-smoothed data, the period of 1 (annual) is more clearly marked. It is still strongest in the beginning of the series. 113**
- Figure 51. Tropical rainforest EVI (smoothed) wavelet spectrum. After the smoothing process, the annual period is more clearly marked. The periods less than one are eliminated. 113**
- Figure 52. Tropical rainforest WDRVI (smoothed) wavelet spectrum. The period of 1 is clearly marked at the beginning of the time series. Stronger compared with the non-smoothed data. 114**
- Figure 53. Irrigated crops EVI wavelet spectrum. The annual period is stronger, but also a period of 0.5 of year (six months) is shown. 115**
- Figure 54. Relative sensitivity of NDVI and WDRVI. Values below 1 means that the NDVI performs better. 117**
- Figure 55. Tropical deciduous forest profiles 2001. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component. 119**

- Figure 56. Tropical deciduous forest profiles 2002. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component..... 119**
- Figure 57. Tropical deciduous forest profiles 2003. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component..... 120**
- Figure 58. Tropical deciduous forest profiles 2004. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component..... 120**
- Figure 59 Tropical deciduous forest profiles 2005. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component..... 121**
- Figure 60. Tropical rain forest profiles 2001. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component. 124**
- Figure 61. Tropical rain forest profiles 2002. The estimated values from the model approach the original data, the first harmonic shows the annual component, the**

second harmonic, the six months component and the third harmonic the four months component. 125

Figure 62. Tropical rain forest profiles 2003. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component. 125

Figure 63. Tropical rain forest profiles 2004. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component. 126

Figure 64. Tropical rain forest profiles 2005. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component. 126

Figure 65. 2001NDVI Fourier a0 parameter. The Fourier a0 parameter is the arithmetic mean for the analyzed year and it is related to the overall greenness of a land cover type. High values are related to evergreen forests with less seasonal variations whereas low values are areas with more seasonal variation. 130

Figure 66. 2001 EVI a0 Fourier parameter. The Fourier a0 parameter is the arithmetic mean for the analyzed year and it is related to the overall greenness of a land cover type. High values are related to evergreen forests with less

seasonal variations whereas low values are areas with more seasonal variation.

..... 131

Figure 67. 2001 WDRVI a0 Fourier parameter. The Fourier a0 parameter is the

arithmetic mean for the analyzed year and it is related to the overall greenness of a land cover type. High values are related to evergreen forests with less seasonal variations whereas low values are areas with more seasonal variation

..... 132

Figure 68. a0 parameter image histogram for the NDVI (a) EVI (b) and WDRVI (c)

..... 133

Figure 69. Amplitude of the first harmonic 2001. Ranges are for low medium and

high amplitudes. High amplitudes are related to vegetation types with strong seasonal component whereas low amplitude values are related to vegetation types with less seasonal component.

137

Figure 70. Amplitude of the first harmonic 2002. Ranges are for low medium and

high amplitudes. High amplitudes are related to vegetation types with strong seasonal component whereas low amplitude values are related to vegetation types with less seasonal component.

138

Figure 71. Amplitude of the first harmonic 2003. Ranges are for low medium and

high amplitudes. High amplitudes are related to vegetation types with strong seasonal component whereas low amplitude values are related to vegetation types with less seasonal component.

139

Figure 72. Amplitude of first harmonic for the year 2004. Ranges are for low

medium and high amplitudes. High amplitudes are related to vegetation types

with strong seasonal component whereas low amplitude values are related to vegetation types with less seasonal component.	140
Figure 73. Amplitude of the first harmonic 2005. Ranges are for low medium and high amplitudes. High amplitudes are related to vegetation types with strong seasonal component whereas low amplitude values are related to vegetation types with less seasonal component.	141
Figure 74. Histograms of the phase of the first harmonic images for the five analyzed years. Notice the shift to the left for the year 2005.	142
Figure 75. Phase of the first harmonic 2001. Ranges are in biweekly period values. Lower values means shift to early biweekly periods and high values means shift to higher biweekly periods.	144
Figure 76. Phase of the first harmonic 2002. Ranges are in biweekly period values. Lower values means shift to early biweekly periods and high values means shift to higher biweekly periods.	145
Figure 77. Phase of the first harmonic 2003. Ranges are in biweekly period values. Lower values means shift to early biweekly periods and high values means shift to higher biweekly periods.	146
Figure 78. Phase of the first harmonic 2004. Ranges are in biweekly period values. Lower values means shift to early biweekly periods and high values means shift to higher biweekly periods.	147
Figure 79. Phase of the first harmonic 2005. Ranges are in biweekly period values. Lower values means shift to early biweekly periods and high values means shift to higher biweekly periods.	148

Figure 80. Results of the 2001 NDVI unsupervised classification of the Fourier	
parameters grouped in six classes.	151
Figure 81. Results of the 2001 EVI unsupervised classification of the Fourier	
parameters grouped in six classes	152
Figure 82. Results of the 2001 WDRVI unsupervised classification of the Fourier	
parameters grouped in six classes.	154

LIST OF TABLES

Table 1. NDVI-based phenological metrics and interpretation (After Reed et al. 1994)	33
<u>Table 2. MODIS Bands source: <http://modis.gsfc.nasa.gov/about/specifications.php></u>	69
Table 3. Sum of squares values. As the number of periods increase, the value of the sum of squares decrease which means a better adjust between the model and the data.....	82
Table 4. Amplitude and phase angle Fourier coefficients for tropical deciduous and tropical rain forests. Except for the constant value which is higher for the tropical rain forest (higher overall values), the amplitude values are higher for the tropical deciduous forest which means more variations.	85
Table 5. Maximum, minimum and range of vegetation indexes of tropical deciduous forest sample.....	93
Table 6. Statistical correlations of vegetation indices versus precipitation (tropical deciduous forest case).	97
Table 7. Maximum, minimum and range vegetation indexes of tropical rainforest sample.....	99
Table 8. Statistical Correlations of vegetation indices versus precipitation (tropical rainforest case).	102

Table 9. Fourier coefficients, Tropical deciduous forest. In bold are shown the mean value (a_0), the amplitude of the first harmonic (c_1), and the phase of the first harmonic (f_1).	122
Table 10. Monthly precipitation (mm). Aquespala weather station. Total precipitation was higher during the years 2005 and 2005 and particularly rainy in the month of June in both cases.	123
Table 11. Fourier coefficients Tropical rain forest. In bold are shown the mean value (a_0), the amplitude of the first harmonic (c_1), and the phase of the first harmonic (f_1).	127
Table 12. Monthly precipitation (mm). Boca del Cerro weather station. 2002 and 2005 were the rainiest years. 2005 was extremely rainy in the month of June.	127
Table 13. Comparison between rainfall (mm) of June and September 2002 and 2005 (Other stations in the study area)	134
Table 14. Surface percentages of the coverage of each class relative to the total surface of the study area	150
Table 15. Error Matrix. accuracy assessment of the 2001 NDVI unsupervised classification	156
Table 16. Accuracy Totals 2001 NDVI unsupervised classification	156
Table 17. Conditional Kappa by category 2001 NDVI unsupervised classification	156
Table 18. Error Matrix. Accuracy assessment of the 2001 EVI unsupervised classification	157
Table 19. Accuracy Totals 2001 EVI unsupervised classification	158

Table 20. Conditional Kappa by category 2001 EVI unsupervised classification ..	158
Table 21. Error Matrix. accuracy assessment of the 2001 WDRVI unsupervised classification.....	159
Table 22. Accuracy Totals 2001 WDRVI unsupervised classification	159
Table 23. Conditional Kappa by category 2001 WDRVI unsupervised classification	159
Table 24. Overall accuracy and overall kappa for the three indices.....	159

LIST OF EQUATIONS

Equation 1. Normalized Difference Vegetation Index (NDVI).....	72
Equation 2. Enhanced Vegetation Index (EVI).....	73
Equation 3. Wide Dynamic Range Vegetation Index (WDRVI)	73
Equation 4. WDRVI from NDVI.....	74
Equation 5. Relative sensitivity equation.....	76
Equation 6. Fourier series approximation equation.....	79
Equation 7. Fourier series equation (simplified).....	83

Chapter 1 Introduction

1.1 Introduction

Tropical forests occupy less than 7% of the terrestrial surface, yet they contain more than half of all plant and animal species (Tucker and Townshend, 2000). Although tropical forests have limited spatial extent (Figure 1 and Figure 2), they play critical roles in global exchanges of energy, in biogeochemical cycling and as reservoirs of biodiversity. As a consequence, they have been a major focus of investigations of global change (Chowdhury 2006; Lambin et al. 2003; Laurance et al. 1998).

During the past several centuries, large areas of tropical forest have been modified by human activities such as agriculture, managed forestry and urbanization (Lambin, 1999). According to the UN-FAO 2005 Global Forest Resources Assessment (2006), it is estimated that around 13 million hectares per year have been lost due to deforestation. However, due to activities such as forest planting, landscape restoration and natural expansion of forests the net loss of forest has been reduced. North and Central America had a net loss of 350,000 ha each one according to the FAO report. Such transformations of land use and land cover (LULC) are of concern because, among other things, they often contribute to increased levels of greenhouse gases and carbon dioxide and result in reduction of biodiversity. (Lambin et al. 2003; Tucker and Townshend 2000; Scholes and van Breemen 1997; O'Brien 1996).

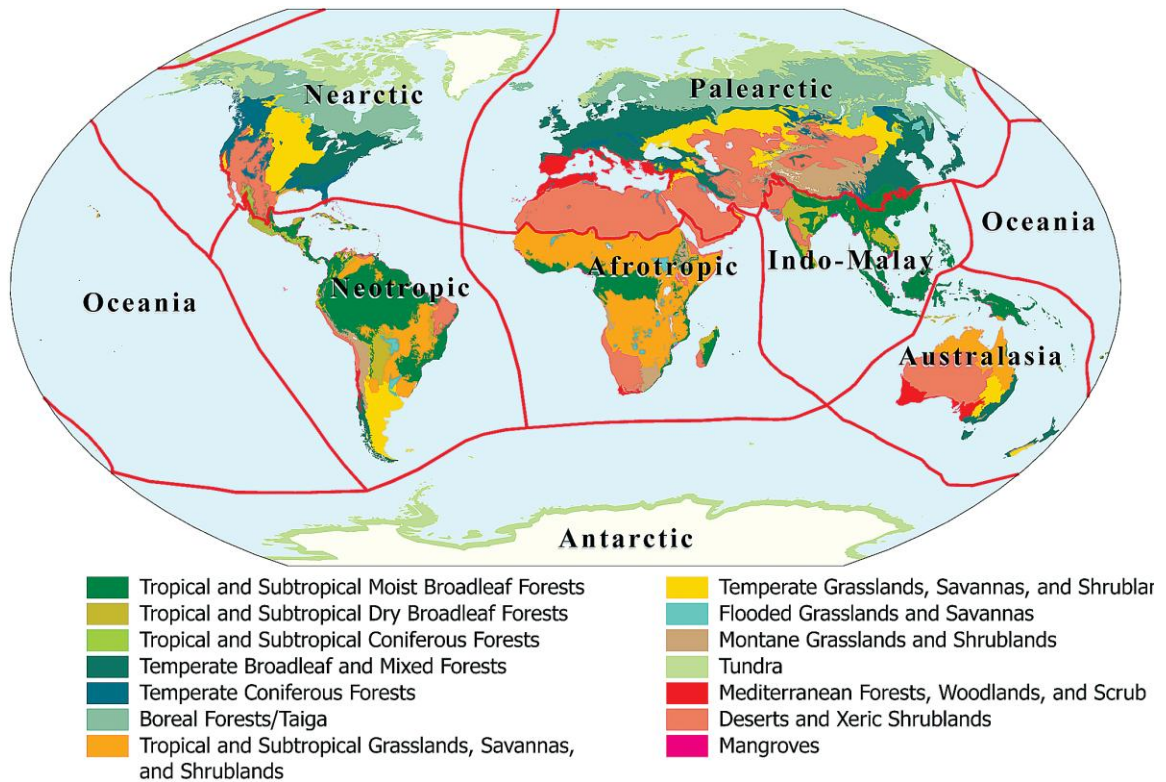


Figure 1. Eight biogeographic realms and fourteen biomes according to Terrestrial Ecoregions of the World: a New Map of Earth (Olson et al. 2001)

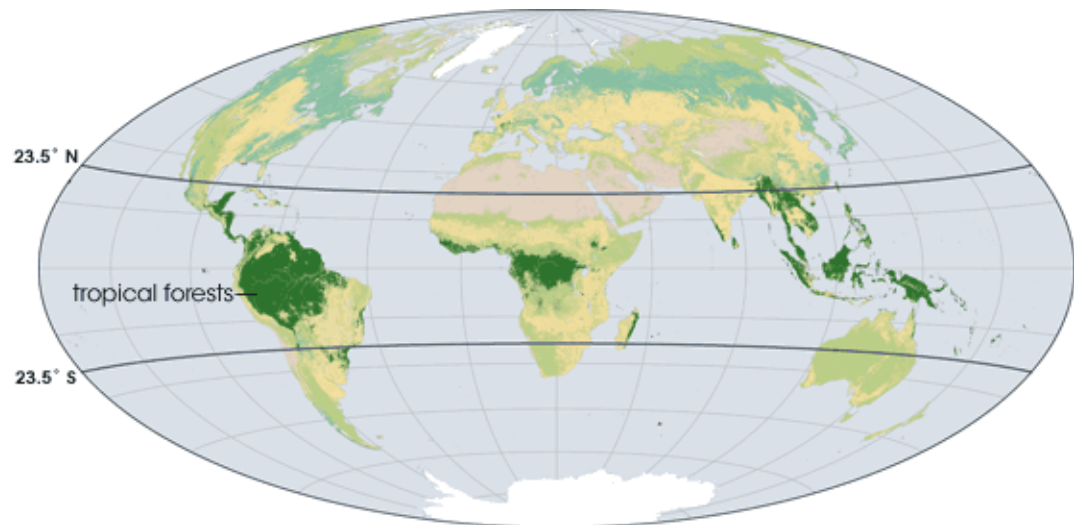


Figure 2. Tropical forests (shown in dark green color) The occurrence between the tropic of Cancer and tropic of Capricorn. Source: <http://earthobservatory.nasa.gov/Features/Deforestation/>

In recent decades, satellite remote sensing has frequently been used to assess the spatial and temporal characteristics of LULC change in tropical forests (e.g., Ichii et al. 2003; Ichii et al. 2002; Eastman and Fulk 1993). Conventional remote sensing approaches for monitoring LULC change are often based on moderate spatial resolution sensors such as those carried on Landsat or SPOT. These satellites, however, have relatively low temporal resolution, and in a typical year can obtain only a few useful (i.e. clear) scenes over tropical areas. Therefore, most often, sensors, such as the NOAA/Advanced Very High Resolution Radiometer (AVHRR) and the TERRA/Moderate Resolution Imaging Spectroradiometer (MODIS), instruments having high temporal resolution, but moderate or coarse spatial resolution, have been employed. LULC change is usually modeled by analysis of changes in vegetation “greenness,” commonly represented by a spectral transformation such as the Normalized Difference Vegetation Index (NDVI) (Bradley et al. 2007; Chowdhury 2006; Pettorelli et al. 2005).

Remote sensing of LULC change in tropical forests has, however, been problematic because the human impact on the landscape is superimposed on an already biologically, spatially and temporally complex ecosystem (Williams-Linera and Meave 2002). The “signal” of anthropogenically-generated LULC change (changing greenness) is embedded in the natural cycles of seasonal (phenological) change that characterize tropical forests, and noise resulting from atmospheric and sensor anomalies. In order to assess and monitor human-induced LULC changes, one must in effect separate the signal of inter-annual LULC change from the normal seasonal changes one would expect to observe in the tropical forest (Bradley et al. 2007; Pettorelli et al. 2005).

This dissertation will explore new and improved methods for analysis of the seasonal variation of land cover in tropical forests using vegetation indices derived from MODIS data. The research will focus on new approaches for using MODIS to assess intra and inter-annual change in tropical land cover that may be related to important changes in the natural environment (e.g., changes in precipitation regimen) and/or human activities (land use).

1.2 Background

Phenology “is the study of the timing of recurrent biological processes such as flowering, budburst, insect hatching, bird nesting, fruit ripening, and leaf fall (so called phenophases)” (Williams-Linera and Meave, 2002). Most often, phenophases occur on a seasonal timescale. In flora, phenophases, specific to each species, generally reflect a combination of interacting environmental factors including latitude, climate (temperature and precipitation regimes), terrain (elevation, slope and aspect) and soils. The phenology of crops and other human-influenced vegetation will, of course, also reflect land management and land use decisions.

As noted above, assessing the phenology of tropical forest vegetation using satellite remote sensing has been especially challenging. Most methods for analyzing multitemporal greenness profiles were developed for mid-latitudes where vegetation phenology tends to be associated with conspicuous seasonal changes in temperature and precipitation (Hill and Donald 2003; Schwartz et al. 2003; Reed, et al. 1994). By contrast, tropical regimes of temperature and precipitation are generally less variable and pronounced than those in other biomes, and variations in plant phenology (and associated

remotely-sensed greenness) are often extremely subtle. Clouds and other atmospheric effects are important issues in tropical regions. Moreover, impacts of human activities (e.g., clearing, grazing, cropping) may be scattered and often occur as small and/or irregular patches interspersed in a larger matrix of forest. When tropical forests are disturbed or abandoned, secondary forests and the process of forest succession may exhibit a unique, unusual behavior as the type and composition of species changes over time (Muchoney et al. 2000). In such circumstances, separating land use change from normal seasonal land cover change and sensor or atmospheric impacts is exceedingly difficult.

The phenology of vegetation as derived from remote sensing is usually depicted by an annual greenness (NDVI) profile (Figure 3). In order to reduce artifacts that might be attributable to sensor or atmospheric anomalies, greenness profiles are often subjected to “smoothing.” Fluctuations in the greenness profile are assumed to indicate the seasonal state and behavior of land cover reflecting biophysical phenomena such as temperature, precipitation and anthropogenic activities (Reed et al. 1994, Schwartz, et al. 2003). Reed et al. (1994) derived a widely-used procedure to extract a set of standardized metrics from annual greenness profiles which will be explained later.

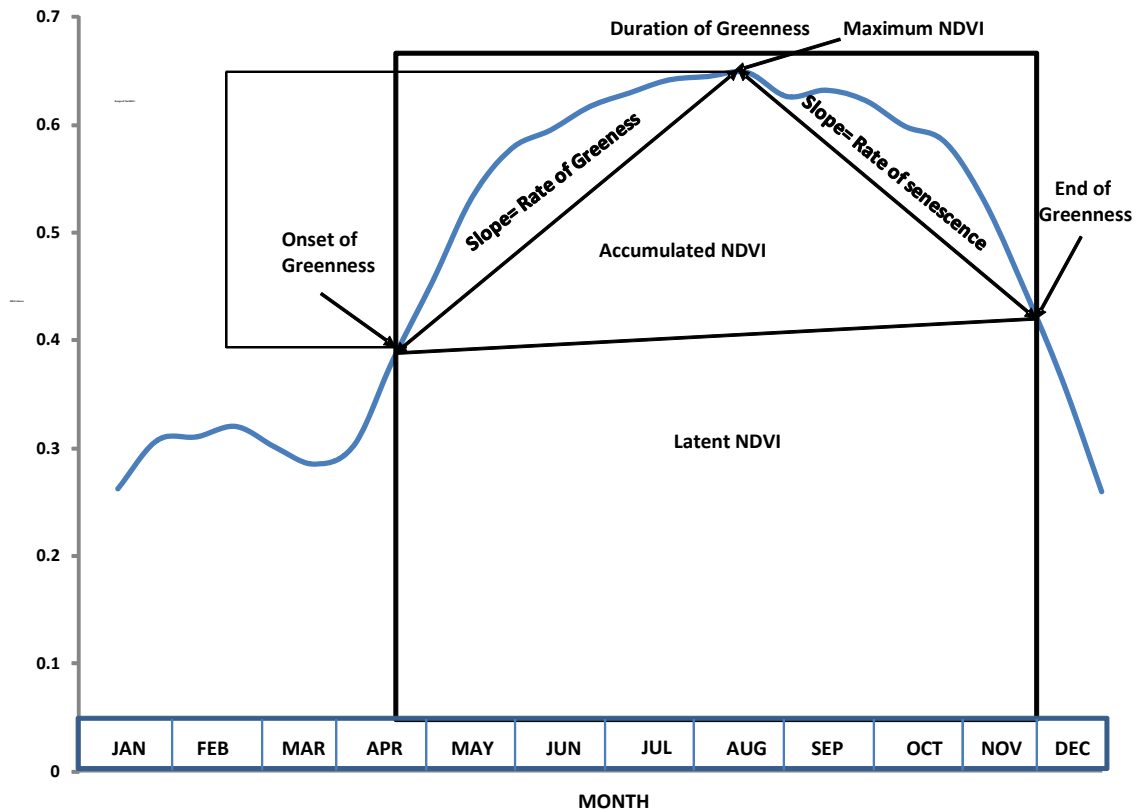


Figure 3. Phenological transition points and phases. (modified from: Zhang, et al. 2001)

Inter-annual changes in greenness profiles (i.e., the timing of important phenological events) may be indicative of either short-term, transient (e.g., drought), or long-term, possibly permanent, (e.g., deforestation, global warming) events, or both (Bradley et al. 2007). Four successive phases of vegetation phenology can be observed in most greenness profiles: green-up, maturity senescence and dormancy (Zhang et al. 2003). Phenological metrics can be extracted and used to model the differences between vegetation types and changes between years (Reed et al. 1994).

Contemporary approaches to analysis of greenness appear to perform reasonably well in mid-latitudes where strong seasonality in climate (temperature and precipitation) can be related to the phenology of vegetation (Hill and Donald 2003; Schwartz et al. 2002; Reed et al. 1994). Some tropical vegetation types, such as tropical deciduous forest or annual crops, can also have such behavior (Figure 4). Tropical rain forests, however, behave quite differently. Tropical regimes of temperature and precipitation are generally less variable and pronounced than those in temperate biomes, and variations in plant phenology (and associated remotely-sensed greenness) are often extremely subtle (Figure 5). Clouds and other atmospheric effects are important issues in tropical regions.

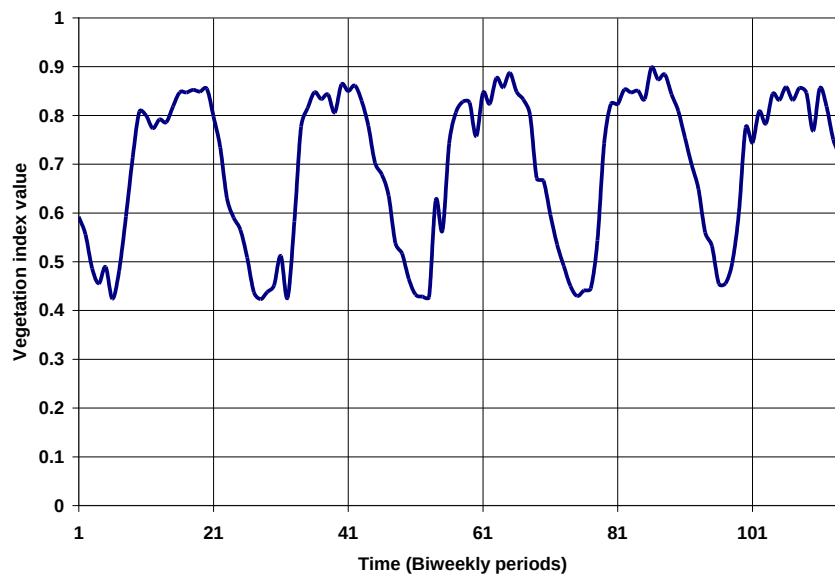


Figure 4. Multi-year raw (non-smoothed) vegetation index profile showing strong seasonality (tropical deciduous forest site) over a five year period starting within January. Greenness increases as the vegetation index approaches a value of 1. In general, peaks coincide with wetter and warmer periods and valleys with dry periods.

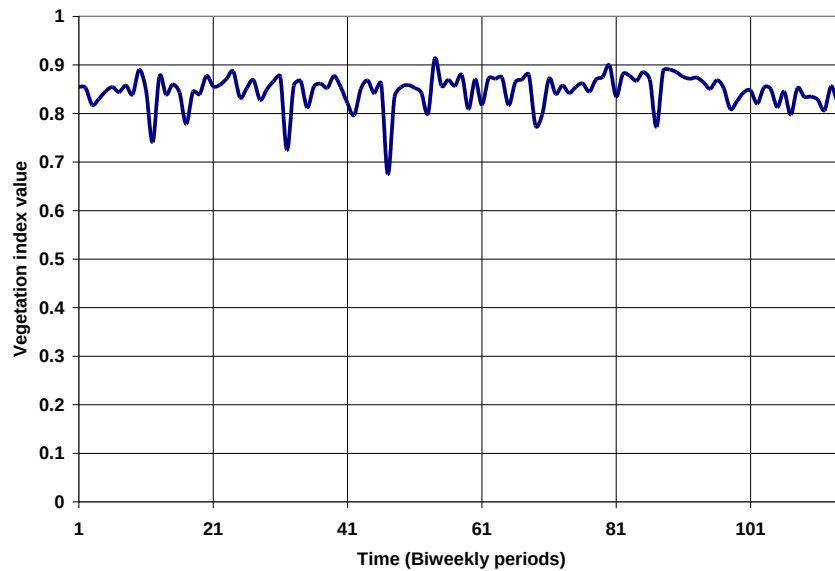


Figure 5. Typical multi-year raw (not smoothed) vegetation index profile showing little seasonality (tropical rain forest site) over a five year period starting with January. Greenness increases as the vegetation index approaches a value of 1. The general trend shows no variation. Local variations may be related to cloud contamination of the imagery. The profile includes five years starting with January.

During the past several decades, many research investigations have been directed towards development of methods to extract LULC information from greenness profiles. A number of authors have used curve fitting functions to reduce noise from vegetation index profiles (Jonsson and Eklundh 2002; Zhang et al. 2003; Jonsson and Eklundh 2004, Beck et al. 2006; Bradley et al. 2007). For example, Zhang et al., (2003) using MODIS data, stated that “vegetation phenology can be represented using series of piecewise logistic functions of time”. They suggested that, since the representation is general, it can be used for a description of the phenology of ecosystems characterized by complex behavior. Eastman and Fulk, (1993), used standardized principal components analysis (PCA) for analysis of change using spatial time series. They argue that the second and subsequent principal components correspond to change elements of successive decreasing magnitude. de Beurs and Henebry (2004) used quadratic models (i.e.

parabolas) to assess land cover change and phenology in semi-arid areas. Although this approach is promising, tropical areas may require more complex models since vegetation index curves of tropical areas do not follow a parabolic shape.

Several investigators have also used classical Fourier analysis methods, suspecting that they may be more sensitive than other methods to seasonal variability in phenology (Moody and Johnson 2001; Azzali and Menenti 2000; Olsson and Eklundh 1994). The Fourier approach decomposes time observations into an average signal depending on the number of harmonics selected as the set of sinusoidal components amplitude and phase (the mean, amplitude and phase are called Fourier parameters). The parameters, summarize the original information contained in the vegetation index profile (Loyarte et al. 2008). The simplicity of the resulting Fourier parameters make it easy to understand differences between different vegetation types and changes over several years by comparing the mean, amplitudes or phases.

In addition to examining alternative approaches to characterizing LULC change in tropical regions based on greenness, research is required to examine and compare other vegetation indices and other sensors (Jonsson and Eklundh, 2002). It is known that the Normalized Difference Vegetation Index (NDVI) which has been used extensively for this type of analysis saturates at moderate to high biomass conditions; hence, the Wide Dynamic Range Vegetation Index (WDRVI) was proposed by Gitelson (2004) as an alternative to increase sensitivity under such conditions. The Enhanced Vegetation Index (EVI) (Huete et al. 2002) is also used widely, especially with MODIS data. Launched in December of 1999, the MODIS sensor, carried on-board the TERRA platform, offers

finer spatial (up to 250 meters) and spectral resolution than the AVHRR and a number of derived standard products including NDVI and the Enhanced Vegetation Index (EVI).

1.3 Research Objectives

Improved methods to characterize tropical LULC change are required. Conclusive information about the use of different greenness indices at different spatial resolutions and about the best methods for seasonal characterization and changes of tropical areas is currently not available. This research will focus on the analysis of greenness profiles obtained using MODIS vegetation indices with 250-meter data. The seasonal behavior of tropical land cover will be modeled using simple and general quantitative models applied to temporal profiles of three different vegetation indices (NDVI, WDRVI and EVI). Seasonal extracted features will be used to generate land use/land cover maps and analyze land use/land cover change and the relationship with precipitation. Fourier series approximation methods will be employed to determine if it is possible to define a specific model with a set of parameters for each land cover type and if the differences between the model's parameters are good indicators of inter-annual change.

Specific objectives are:

1. To establish the mean (“normal”) seasonal variation of tropical land cover types as detectable with MODIS imagery
2. To compare the sensitivity of the NDVI, WDRVI and EVI for different land cover types, and.

3. To determine if the Fourier parameters used as seasonal metrics are sensitive for different tropical vegetation types and indicators of vegetation changes or climate variability.

1.4 Study Area

This research will be carried within the Mayan forest of southern Mexico and Northwest Guatemala (Figure 6). The Mayan forest, one of the most important northern tropical areas in the continent, is an area with a large expanse of undisturbed tropical vegetation including several biosphere reserves (Hayes et al. 2002). The Maya Biosphere Reserve established in 1990 represents the largest contiguous area of tropical forest remaining in Central America (Hayes et al. 2002). This is an area covered by a variety of land cover types including tropical rainforest, secondary vegetation in several stages of succession, and tropical grasses resulting from the conversion of the original vegetation and wetlands. In the high elevations, between 1000 and 2000 meters above sea level, temperate forest is the main vegetation type with cloud forest and mixed forests as transition vegetation types.

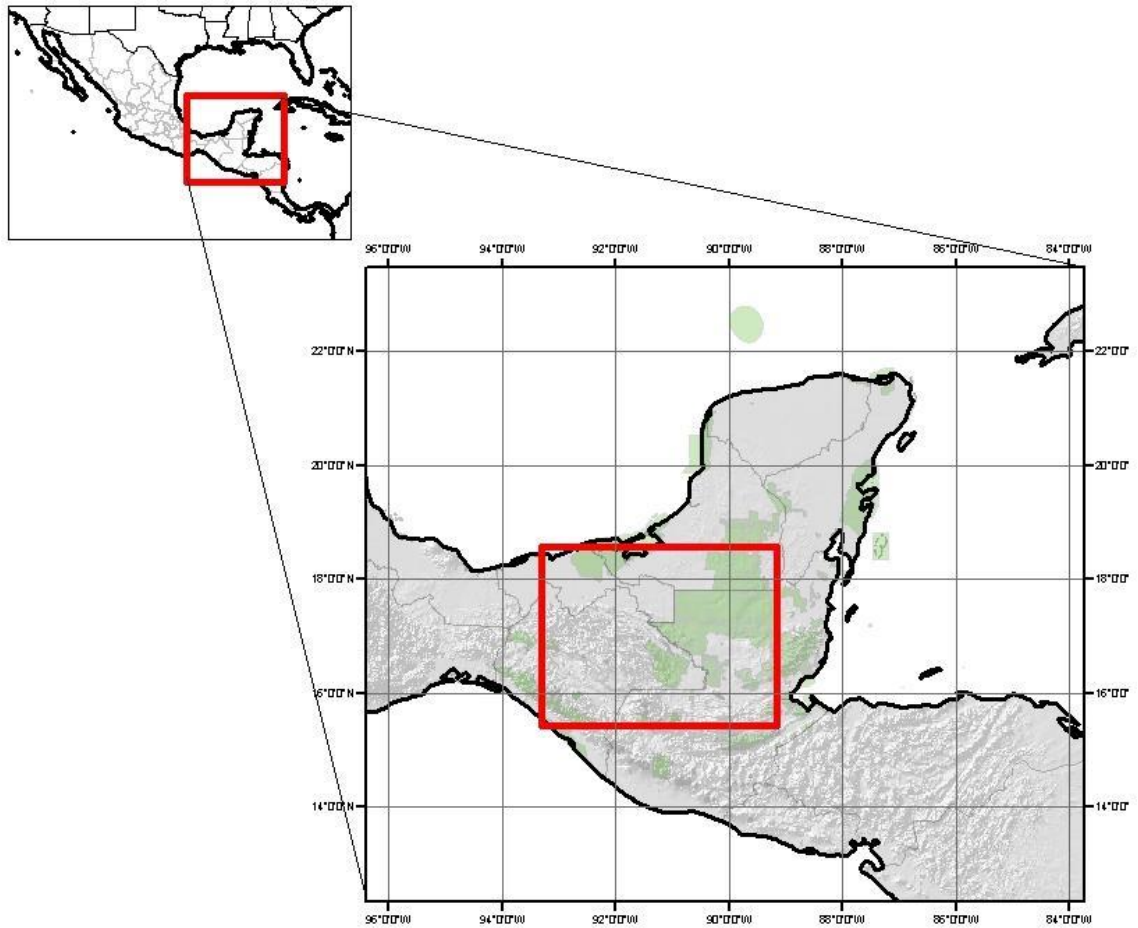


Figure 6. Study area: The red square portrays the extent of the study area covering southeastern Mexico-northern Guatemala. The image is a shaded relief map showing in green shades the major natural protected areas.

The region has had a long history of human occupation and was the heartland of Mayan civilization about 1,100 years ago. The Mayan use of the tropical forest had an important impact that is reflected even today since many areas are considered as late secondary instead of original forests (Brown and Lugo 1990) and many traditional agriculture practices survive. In more recent times, extensive areas of tropical forest have been converted to pasture and other agricultural activities.

Many remote sensing-based studies of land use and land cover have been carried out in Mexico, specifically in the area of the Mayan Forest. Most of these have utilized

Landsat imagery (de Jong et al. 1999; Cairns et al. 2000; Ochoa-Gaona and Gonzalez-Espinoza 2000; Turner et al. 2001; Lunetta et al. 2002; Galicia and Garcia-Romero 2007; Porter-Bolland et al. 2007). A few studies using multi-temporal AVHRR data have been conducted for the whole country (Mora and Iverson 1997; Ortega-Huerta et al. 2000) but these have been limited to analyzing LULC variation for one year only. Mora and Iverson made one of the first attempts to use seasonal components in a vegetation/land cover classification. Lannom et al. (2001) mapped the percent of forest area and forest cover types for Mexico and Central America, and Muchoney et al. (2000) used MODIS 1 km. to characterize regional vegetation and land cover for rapid ecological assessment. Studies using MODIS have employed mostly 1Km. or 500-meter spatial resolution data (Zhang et al. 2003; Myneni et al. 2002; Fisher and Mustard 2007). In areas such as Southern Mexico and Central America where the forest remnants are highly fragmented (Mayaux et al. 2004), use of the highest MODIS spatial resolution data (250-meter) is required.

1.5 Synopsis of Methods

This research is based primarily on the MODIS13 16-day vegetation index dataset, a set of NDVI maximum-value composite images for the years 2001-2005 obtained from the Earth Observing System Data Gateway (WIST) https://lpdaac.usgs.gov/lpdaac/get_data/wist. Analysis was carried out as follows:

- (1) Two vegetation indices (NDVI and EVI) were extracted from the MODIS dataset and stacked by year. The WDRVI was calculated from the NDVI.

(2) Samples of key vegetation types (tropical rainforest, tropical deciduous forest, temperate forest, secondary forest, annual crops, grass and pasture) were identified using higher resolution Landsat Enhanced Thematic Mapper (ETM) imagery. The Regions of interest (ROI) samples were stacked to obtain an annual profile of vegetation indices from which greenness profiles (for vegetation type and year) were extracted.

(3) In order to evaluate the performance of the three vegetation indices (NDVI, EVI and WDRVI) a wavelet analysis was carried out to evaluate the periodicity of the data. Morlet wavelet analysis was used to determine if there was a periodic behavior (related to seasonality), and if so, how strong this periodicity was when it occurred. This was done in order to define which of the indices provides more information in terms of seasonality. Statistical correlations between the indices and precipitation as well as a sensitivity index proposed by Viña et al. (2004) were used to compare how the indices behave.

(4) Vegetation index profiles were analyzed using a temporal feature extraction known as Fourier series approximation (Olsson and Eklundh 1994; Moody and Johnson 2001; Jakubauskas et al. 2001) which decomposes a time series of signals into a sum of sine and cosine functions of different periods until the best fit is approached. The output of this method provides a set of optimal function parameters (mean amplitude and phase angle by harmonics) that can be related to the annual and inter-annual properties of each land cover type. The modeling describes the main components of the whole curve (optimal parameters of the function) rather than specific break points related to the start/end of the growing season. Therefore any kind of curve shape can be modeled, not only the ones that exhibit a strong seasonal component at the same time, the procedure

smoothes the curve; hence spurious data is eliminated. Since the parameters (Fourier coefficients) describe the contribution of part of the function at each period, they are used to evaluate differences by comparing the same parameter value between years and to perform a land cover classification based on temporal characteristics. Changes in amplitude and/or shift in phase angle of a particular period can be related to changes in structure and function of the ecosystem, due to natural processes such as climatic variations, natural succession or human-related processes like land-use management (deforestation, forest degradation, forest fragmentation).

(5) Fourier series approximation was used on a pixel by pixel basis in order to obtain images which show the spatial pattern of each parameter (mean, amplitude and phase angle) and determine the differences between years. The Fourier parameters were input to an unsupervised classification in order to obtain a land use/land cover product (one per vegetation index) which was then compared with ground truth data. Results show which index performs better for a rapid assessment evaluation based on temporal characteristics of the land cover.

1.6 Implications of Research

This research is expected to lead to better understanding of the relationships between multi-temporal vegetation index profiles derived from coarse-resolution satellite imagery and natural dynamics in tropical forests. More specifically, the advantages and disadvantages of using different vegetation indices will be defined. The research will also contribute to a better understanding of means for monitoring the seasonal dynamics of tropical regions at regional scales and identifying intra and inter-annual changes that may

be related to events such as climate change or human-induced land use transformations. Such efforts are critical to support biodiversity conservation, sustainable development and management of protected areas in tropical biomes.

1.7 Organization of the Dissertation

This thesis is organized in five chapters. Chapter 1 provides the overall scope and objectives of the project. In Chapter 2, key background literature pertaining to the characteristics and importance of tropical forests, the use of multitemporal remote sensing to monitor LULC change in tropical areas is reviewed. Chapter 3, presents a detailed description of the study its particularities, complexity and importance in the global and local context. Chapter 4 focuses upon the research methods including a detailed description of the datasets used and preprocessing and processing methods. Results of the research experiments are presented in Chapter 5. This chapter includes comparison of the research results with other pertinent studies and evaluation of the findings. The comparison of vegetation indices and the results of applying the Fourier series approximation method are shown in graphs and tables for the key vegetation types. In addition, a per-pixel analysis of Fourier parameters and also the land cover/land use classification are presented. Chapter 6 comprises a summary of the investigation and its implications, including suggested avenues for future research.

References

- Azzali, S. and M. Menenti. 2000. Mapping vegetation-soil-climate complexes in southern Africa using temporal Fourier analysis of NOAA-AVHRR NDVI data. *International Journal of Remote Sensing* 21(5):973-996.
- Bradley, B.A., R.W. Jacob, J.F. Hermance, and J.F. Mustard. 2007. A curve fitting procedure to derive inter-annual phenologies from time series of noisy satellite NDVI data. *Remote Sensing of Environment* 106(2):137-145.
- Brown, S. and A.E. Lugo. 1990. Tropical Secondary Forests. *Journal of Tropical Ecology* 6(1):1-32.
- Chowdhury, R.R. 2006. Driving forces of tropical deforestation: The role of remote sensing and spatial models. *Singapore Journal of Tropical Geography* 27:82-101.
- de Beurs, K.M. and G.M. Henebry. 2004. Trend analysis of the Pathfinder AVHRR Land (PAL) NDVI data for the deserts of central Asia. *Geoscience and Remote Sensing Letters, IEEE* 1(4):282-286.
- de Jong, B.H.J., M.A. Cairos, P.K. Hagerty, N. Ramirez-Maciel, S. Ochoa-Gaona, J. Mendoza-Vega, M. Gonzalez-Espinosa, and I. March-Mifsut. 1999. Land-use change and carbon flux between 1970s and 1990s in central highlands of Chiapas. *Environmental Management* 23(3):373-385.
- Eastman, R.J. and M. Fulk. 1993. Long Sequence Time Series Evaluation Using Standardized Principal Components. *Photogrammetric Engineering & Remote Sensing* 59(8):1307-1312.

- Gitelson, A.A. 2004. Wide Dynamic Range Vegetation Index for Remote Quantification of Biophysical Characteristics of Vegetation. *Journal of Plant Physiology* 161:165-173.
- Hayes, D.J., S.A. Sader, and N.B. Schwartz. 2002. Analyzing a forest conversion history database to explore the spatial and temporal characteristics of land cover change in Guatemala's Maya Biosphere Reserve. *Landscape Ecology* 17:299-314.
- Hill, M.J. and G.E. Donald. 2003. Estimating spatio-temporal patterns of agricultural productivity in fragmented landscapes using AVHRR NDVI time series. *Remote Sensing of Environment* 84(3):367-384.
- Huete, A., K. Didan, T. Miura, E.P. Rodriguez, X. Gao, and L.G. Ferreira. 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment* 83:195-213.
- Ichii, K., A. Kawabata, and Y. Yamaguchi. 2002. Global correlation analysis for NDVI and climatic variables and NDVI trends: 1982-1990. *International Journal of Remote Sensing* 23(18):3873-3878.
- Ichii, K., M. Maruyama, and Y. Yamaguchi. 2003. Multi-temporal analysis of deforestation in Rondonia state in Brazil using Landsat MSS, TM, ETM+ and NOAA AVHRR imagery and its relationship to changes in the local hydrological environment. *International Journal of Remote Sensing* 24(22):4467-4479.
- Jakubauskas, M.E., D.R. Legates, and J.H. Kastens. 2001. Harmonic Analysis of Time-Series AVHRR NDVI Data. *Photogrammetric Engineering & Remote Sensing* 67(4):461-470.

- Jonsson, P. and L. Eklundh. 2002. Seasonality extraction by function fitting to time-series of satellite sensor data. *IEEE Transactions on Geoscience and Remote Sensing* 40(8):1824-1832.
- Jonsson, P. and L. Eklundh. 2004. TIMESAT a program for analyzing time-series of satellite sensor data. *Computers & Geosciences* 30:833-845.
- Lambin, Eric F. 1999. Monitoring forest degradation in tropical regions by remote sensing: some methodological issues. *Global Ecology and Biogeography* 8:191-198.
- Lambin, E.F., H.J. Geist, and Lepers.E. 2003. Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environmental Resources* 28:205-241.
- Lannom, K.B., D.L. Evans, and W.H. Cooke. 2001. Forest Mapping of Central America and Mexico with AVHRR Data. *Geocarto International* 16(1).
- Laurance, W.F., S.G. Laurance, and P. Delamonica. 1998. Tropical forest fragmentation and greenhouse gas emissions. *Forest Ecology and Management* 110:173-180.
- Loyarte, M.M.G. and M. Menenti. 2008. Impact of rainfall anomalies on Fourier parameters of NDVI time series of northwestern Argentina. *International Journal of Remote Sensing* 29(4):1125-1152.
- Mayaux, P., E. Bartholome, S. Fritz, and A. Belward. 2004. A new land-cover map of Africa for the year 2000. *Journal of Biogeography* 31:861-877.
- Moody, A. and D.M. Johnson. 2001. Land-Surface Phenologies from AVHRR Using the Discrete Fourier Transform. *Remote Sensing of Environment* 75(3):305-323.

- Mora, F. and R. Iverson. 1997. Dynamic stratification of the landscape of Mexico: analysis of vegetation patterns observed with multitemporal remotely-sensed images. *Geocarto International* 12(2):73-87.
- Muchoney, D., J. Borak, H. Chi, M. Friedl, S. Gopal, J. Hodges, N. Morrow, and A. Strahler. 2000. Application of the MODIS global supervised classification model to vegetation and land cover mapping of Central America. *International Journal of Remote Sensing* 21:1115-1138.
- Myneni, R.B., S. Hoffman, Y. Knyazikhin, J.L. Privette, J. Glassy, Y. Tian, Y. Wang, X. Song, Y. Zhang, G.R. Smith, A. Lotsch, M. Friedl, J.T. Morisette, P. Votava, R.R. Nemani, and S.W. Running. 2002. Global products of vegetation leaf area and fraction absorbed PAR from year one of MODIS data. *Remote Sensing of Environment* 83(1-2):214-231.
- O'Brien Karen L. 1996. Tropical deforestation and climate change. *Progress in Physical Geography* 20(3):311-335.
- Olson, M., E. Dinerstein, E. Wikramanayake, N. Burgess, G. Powel, E. Underwood, J. D'Amico, H. toua, H. trand, J. Morrison, C. Loucks, T. Allnutt, T. Ricketts, Y. Kura, J. Lamoreux, W. Wettengel, P. Hedao, and K. Kassem. 2001. Terrestrial Ecoregions of the World: A New Map of Life on Earth . *BioScience* 51(11).
- Olsson, L. and L. Eklundh. 1994. Fourier Series for analysis of temporal sequences of satellite sensor imagery. *International Journal of Remote Sensing* 15(18):3735-3741.

- Ortega-Huerta, M.A., E. Martinez-Meyer, S.L. Egbert, K.P. Price, and A.T. Peterso.
2000. Mapping the Land Cover of Mexico Using AVHRR Time-Series Data Sets.
Geocarto International 15(3):7-19.
- Pettorelli, N., J.O. Vik, A. Mystereud, J.M. Gaillard, and C.J.a.S.N.C. Tucker. 2005.
Using the satellite-derived NDVI to assess ecological responses to environmental
change. *Trends in Ecology and Evolution* 20(9):503-510.
- Reed, B.C., J.F. Brown, D. VanderZee, T.R. Loveland, J.W. Merchant, and D.O. Ohlen.
1994. Measuring phenological variability from satellite imagery. *Journal of
Vegetation Science* 5:703-714.
- Scholes.R.J. and N. van Breemen. 1997. The effects of global change on tropical
ecosystems. *Geoderma* 79:9-24.
- Schwartz, M.D., B.C. Reed, and M.A. White. 2003. Assessing Satellite-Derived start-of-
season measures in the conterminous USA. *International Journal of Climatology*
22:1793-1805.
- Tucker, C.J. and J.R.G. Townshend. 2000. Strategies for monitoring tropical
deforestation using satellite data. *International Journal of Remote Sensing*
21(6&7):1461-1471.
- UN FAO. Global Forest Resources Assessment 2005. 2006. Rome.
- Williams-Linera, G. and J. Meave. 2002. Patrones Fenologicos. *In Ecologia y
conservacion de bosques neotropicales*, eds. M.R.Guariguata and G.H.Kattan.
407-31. Libro Universitario Regional: Costa Rica.

Zhang, X., M.A. Friedl, C.B. Schaaf, A.H. Strahler, J.C.F. Hodges, F. Gao, B.C. Reed, and A. Huete. 2003. Monitoring vegetation phenology using MODIS. *Remote Sensing of Environment* 84(3):471-475.

Chapter 2 Background

2.1 Introduction

This dissertation focuses on remote sensing of tropical forests. Tropical forests are defined here to include both tropical rain forests, the most important land cover in terms of biomass and extent, and associated land cover types such as savannas, tropical deciduous forests and temperate forests. The later are typically interspersed among tropical rainforests, their locations influenced by local topography. Transformation of tropical forest to other land cover affects the structure, morphology and physiology of vegetation, biodiversity, nutrient cycling and climate (O'Brien 1996).

A vast literature deals with land use/land cover change in tropical forests. Nevertheless, there are significant disparities in estimates of rates of land use/land cover change. In recent decades, satellite remote sensing has frequently been used to assess the spatial and temporal characteristics of land cover and land use in tropical forests (Eastman and Fulk, 1993, Ichii, et al., 2002; Ichii, et al. 2003). In this chapter I provide background information on tropical forest in Central America and discuss precious attempts to use satellite remote sensing in monitoring land use and land cover change.

2.1.1 Climate in the Tropics

Seasonal changes in the tropics show little variation in mean temperature, and day/night length (Nieuwolt 1977). This is a result of a small seasonal variation in the incident radiation over the Earth's surface. In contrast, precipitation shows a clear seasonal pattern. Precipitation patterns are related in a general way to the north-south

migration of the inter-tropical convergence zone (ITCZ) through the year. Tropical areas tend to have high and continuous precipitation all year, although the area between 3° and 10° north or south of the equator shows two dry seasons and two rainy seasons. Inter-tropical areas between the Equator and 23° 27' north or south usually have one precipitation peak during the summer (Nieuwolt, 1977). Also annual and inter-annual precipitation in the tropics varies by year, decade or even century. The most well-known influence related to variation is the periodic oscillation of the ocean-atmosphere system in the Pacific Ocean known as the El Niño Southern Oscillation (ENSO) (Curtis 2008). Figure 7 shows average monthly data from a weather station representative of a humid-tropical area. Temperature and high precipitation values increase during the period from May to October.

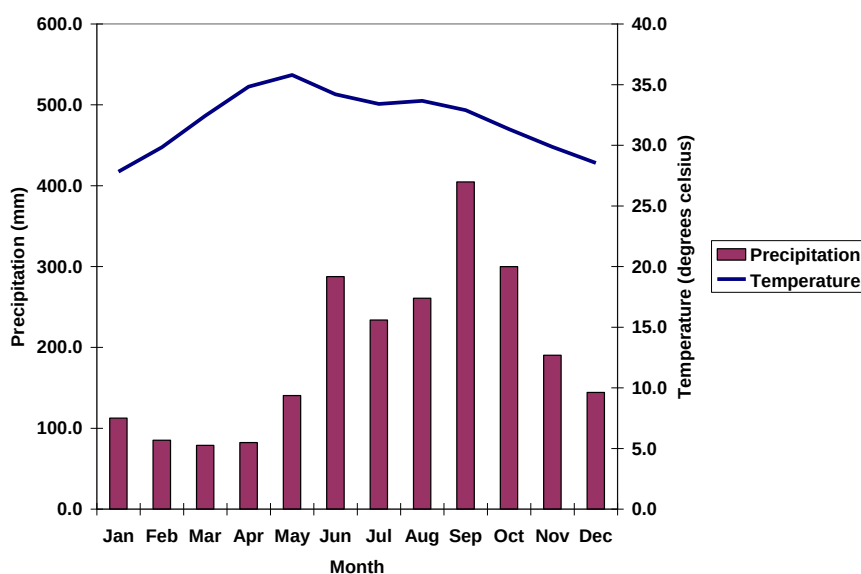


Figure 7. Temperature and precipitation historical monthly averages (Boca del Cerro weather station in southeastern Mexico close to the Guatemala Border). High mean temperatures typical from tropical regions. Precipitation regimen show higher values during the summer months and a local minima between the months of June and September.

Note the relative dry period in July and August, called the midsummer drought period, which is a particularly interesting phenomenon in Southern Mexico, Central America and parts of the Caribbean.

2.1.2 Carbon cycling in tropical forests

Photosynthesis is fundamental for plant growth. Carbon dioxide (CO₂) is fixed during this process and is transformed into carbon compounds, essential for building vegetative leaves. Regulation of the carbon budget is controlled not only by the photosynthetic rate of the leaves but also by the amount of light that the leaves can intercept. The capacity of leaves to intercept light and therefore gain carbon is influenced by the geometric disposition of the leaves and the biomass of the plant (Chazdon and Montgomery 2002). According to Ichii et al. (2005), there are still large uncertainties regarding the processes controlling the carbon budget of tropical forests. Carbon budgets of tropical forests are considered to account for about 20% of global terrestrial carbon stocks. Conversion from natural vegetation to croplands, results in a loss of CO₂ from plants and soil to the atmosphere (Scholes and van Breemen 1997). On the other hand, tropical secondary forests have a high rate of carbon fixation (Guariguata and Ostertag 2002).

Considering the role of tropical ecosystems in the global carbon cycle, improved understanding of current variations in the tropical ecosystems and its response to environmental variations is important for predicting climate changes since many of the estimates are based on limited models. Improved methods of land cover mapping and land cover change can contribute significantly to a more realistic estimation of carbon

budgets. Predicting the rate of carbon assimilation by an ecosystem requires more than merely knowing the species composition and structure. It is important to also know the seasonal development of vegetation and to assess land use and land cover change (Scholes and van Breemen 1997).

2.1.3 Forest Degradation and Forest Fragmentation

According to Lambin (1999) forest degradation is a process leading to a temporary or permanent deterioration in the density or structure of vegetation cover or its species composition. Tropical deforestation, as the loss of forest cover in tropical areas, affects hydrology balance, genetic resources, and global cycles of carbon and other elements. It is one of the main causes of biodiversity loss around the world (Kattan 2002). Deforestation usually results in fragmented landscapes where the remnants of the original vegetation are embedded in a matrix of transformed habitats (Blanco and Garcia 1997). Tropical forest fragmentation can lead to the modification of the environment and local climate. Replacement the original forest cover with pasture causes an increase in soil surface temperature and evapotranspiration and a decrease in precipitation (Kattan 2002). Besides the physical changes, habitat fragmentation resulting from deforestation can lead to the extinction of many species locally and regionally (Imbernon and Branthomme 2001). Species extinction results from two phenomena on two different spatial scales. First, once the forest cover is reduced, the diversity of habitats and the total area of available habitat are reduced as well. Secondly, forest fragmentation leaves isolated populations inside the remaining patches. As a result of the isolation, these populations tend to be small. Demographic factors (lower number of individuals) and the

occurrence of random processes (recurrence of natural perturbations) further increase extinction risk within these populations (Kattan 2002).

Habitat fragmentation is defined as the disruption of continuity in a pattern or process. Habitat fragmentation reduces the total amount of habitat type and generates smaller and isolated patches (Echeverria 2007; Kattan 2002). Clearing of tropical forests for pastures, farmlands and other human activities, is a major source of greenhouse emissions which contribute to global warming (Laurance et al. 1998). Deforestation and forest fragmentation lead to increased levels of atmospheric CO₂ as well as other trace gasses. This is due to the fact that carbon fixation is higher in forests than in the pastures and agricultural land, which usually replace the original forest (Skole and Tucker 1993; Tucker and Townshend 2000). With about 70% of biomass burning occurring in the tropics, conversion of tropical forest to pasture land and agriculture lands is considered a major source of these emissions (Laurence et al. 1998).

2.1.4 Succession

By contrast with temperate forests, the succession process in tropical rain forests is highly dynamic (Bazzaz and Picket 1980). Disturbances influence succession by changing the levels of resources available. Disturbances can be both human and environmentally-initiated and range in impact from small to large scale. Tropical secondary forests which are defined as those resulting from human disturbance (Brown and Lugo 1990), are important components of tropical vegetation. With the exception of a few places and protected areas, many countries have a higher prevalence of secondary, rather than mature or primary forests (Guariguata and Ostertag 2002). Therefore, it is

very important to understand how to manage secondary forests properly. Secondary vegetation resulting from human activities occupies large areas, which are frequently disregarded by the public and are considered useless and thus minimally managed. Usually these areas result from agricultural abandonment of previously cleared forest. Slash and burn is the principal method utilized for clearing forest for agricultural use. This technique is used to clear areas up to several hectares over the course of one to three years (Brown and Lugo 1990). Cases of shifting cultivation mixed with more permanent agriculture such as pastures or plantations can occur. Secondary forests accumulate biomass more rapidly than mature forests. In small clearings the recruitment of successional species is rapid and the site quickly becomes covered by pioneer species. Within a few years (less than a decade) the succession process causes secondary forests to resemble mature forest (Bazzaz and Picket 1980). In the case of large scale clearings the sites lose nutrients and incur other modifications in the soil as well. The return of species from the original primary forest is slow in these cases. Repeated burning may increase the possibility of grasses dominating and inhibit the establishment of tree saplings.

In terms of carbon stock processes, it is well known that the main sinks are the oceans and temperate and boreal forests (Lucas et al. 2000). The role of post-clearing succession in tropical areas as a carbon sink is not well known. Lucas, et al. (2000) argue that these areas could serve as an important carbon sink. The age of the forest and the number of times that it has been cleared and used for agricultural or pastoral purposes are related to the rate at which carbon is sequestered by secondary forests (Nelson et al. 2000). Thus, it is very important to determine the land use history. Secondary forests are

dramatically increasing in area throughout the world's tropical areas. Currently, most studies and conservation efforts are oriented toward mature forests. It is critically important to consider the characteristics and value of secondary forests as many conservation efforts depend on them (Brown and Lugo 1990; Guariguata and Ostertag 2002).

Secondary forests are also important because they are often close to human settlements. They provide wood, fruits, medicinal plants, construction materials and valuable resins (Brown and Lugo 1990). Additionally, they serve to retard soil erosion, protect water quality, moisture and organic matter which are important for the conservation of biodiversity in tropical areas (Guariguata and Ostertag 2002). The pressure to exploit mature forests will decrease if secondary forests are managed in a sustainable way (Brown and Lugo 1990). According to Nelson, et al. (2000), an abandoned piece of agricultural or pasture land replaces 25% of the original biomass found in the primary forest within 8 years.

Tropical areas have been widely affected by changes in land cover at an accelerated rate. These changes are closely linked to socioeconomic development (Allen and Barnes 1985; Zhang et al. 2003). As populations grow and develop so too does the demand for clearing land, grazing and raising crops. When lands are disturbed or abandoned, secondary forests and the process of forest succession may exhibit a unique, unusual phenology as the type and composition of species changes over time (Muchoney et al. 2000). Remote sensing of secondary forest could shed valuable light on the status and changes in tropical environments.

2.2 Multitemporal Remote Sensing

Satellite images are one of the most important information sources for tropical areas (Toumisto et al. 1994), and have often been used to evaluate and monitor the behavior of tropical forest

Few studies have been focused on the temporal behavior of tropical vegetation. Research is needed to relate the response of vegetation to plant phenology. Most studies of remote sensing phenology have been conducted in temperate areas and usually there are clear and contrasting seasonal periods (cold/warm or dry/wet) (Reed et al. 1994; Moody and Johnson 2001; Schwartz et al 2002; de Beurs and Henebry 2004; Stöckli and Vidale 2004; Reed et al 2006; Bradley et al. 2007). In these studies, the goal is usually to find the inflexion points related to changes in vegetation productivity which are related to an increase of greenness called start of the season (SOS), or the senescence called end of the season (EOS). Several studies done in tropical areas have shown that even in areas where the temperature and precipitation are relatively constant all the year, there are slight temporal variations in precipitation. Secondary vegetation and annual and perennial crops respond differentially to these variations (Jönsson and Eklundh 2002; Kobayashi and Dye 2005; Huete et al 2006; Hess et al. 2009; Pennec et al. 2001).

The temporal domain of satellite imagery holds rich information on ecosystem behavior and serves as an important source of data for vegetation mapping and monitoring (Olsson and Eklundh 1994). Most multitemporal studies have used low spatial resolution data derived from AVHRR data. Data from the MODIS sensor, which has, a higher spatial resolution (250m) and better geometry is being used frequently at present. Other satellite imagery such as Landsat TM has limitations related to cloud

cover, spatial coverage and cost when analyzing large areas. Much of the Landsat and multitemporal work is still oriented towards differentiating types of forested land cover types. Monitoring deforestation rates and their impact on regional and global climate and biodiversity require frequent observations (Nelson et al. 2000).

2.3 Remote Sensing Phenology

Remote sensing has been used to study vegetation phenology on both continental and global scales. Intra-annual variability in terrestrial plant phenology, is an important key in the dynamics of surface-atmosphere carbon fluxes, and other biogeochemical cycles (Moody and Johnson 2001). Vegetation phenology can provide base line data to monitor changes in vegetation associated with land use conversions regardless of other events such as drought, fire and climate variations (Moody and Johnson 2001). Vegetation phenology is potentially a very useful complement to the traditional characterization of physiognomic and floristic composition (Hoare and Frost 2004).

Remote sensing of phenology is usually modeled by time-trajectories where for each pixel, a temporal profile or “greenness” curve is built using a spectral transformation such as the Normalized Difference Vegetation Index (NDVI). These temporal profiles are used to categorize the surface cover into distinct functional vegetation types (i.e. land cover classification based on seasonal properties) (Loveland et al. 1991). As will be explained later, those profiles have specific features which can be related to phenological characteristics of vegetation.

In mid and high latitudes, plant growth and reproduction rates are mainly related to temperature and photoperiod. In the tropics photoperiod and temperature are relatively

constant. Plant behavior directly correlates to seasonal changes in rainfall (Wright and Cornejo 1990).

de Beurs and Henebry (2005) used the term land cover phenology as a way to approach the use of time series data for vegetation characterization and classification. Land cover phenology is defined as: “the study of the spatio-temporal patterns of vegetated land surface as observed by synoptic sensors at spatial resolutions and extents relevant to meteorological processes in the atmospheric boundary layer”. Thus, adopting this concept can be particularly useful in tropical-humid environments since it shows seasonal trends in large heterogeneous areas such as tropical rain forests which often include complex matrices of patches that result from human activities (e.g. grazing, cropping, and succession).

2.3.1 Phenological Variables

Reed et al. (1994) derived a procedure to extract a set of standardized metrics from greenness curves, each one related to a phenological interpretation. The metrics appear to perform well in circumstances where there is a strong seasonality which can be related to the phenology of vegetation (i.e., in climates exhibiting a clear seasonality related to warm-cold temperatures and dry-rainy precipitation regimes) (Reed et al. 1994; Schwartz et al. 2003) Reed utilized a delayed moving average (DMA) in contrast to the smoothed NDVI time-series. NDVI data values are compared to the average from the previous (user-defined) n NDVI observations to identify departures from an established trend (Reed et al. 1994). The DMA value serves as a predicted value to which the real NDVI values are compared. A trend change is detected where the NDVI value departs

from (becomes greater than) the value of the moving average. An example of this is when low NDVI values are predicted by the moving average but the actual NDVI values are higher. This departure is labeled as the start of the growing season (SOS). The end of the growing season (EOS) is calculated in a similar manner with the moving average running in the opposite direction. Duration of growing season is defined as the difference between the time of EOS and SOS. The peak of the growing season is simply the time of the maximum NDVI. Several other metrics can then be derived, including the rate of green-up (slope from SOS to peak), rate of senescence (slope from peak to EOS), and total integrated NDVI (area under the curve). Table 1, summarizes the derived metrics and their meaning (see also Figure 3) as proposed by Reed et al. (1994).

Data on phenology and distribution of vegetation are important because vegetation strongly influences animal distribution and dynamics (Pettorelli et al. 2005).

Phenological Metric	Phenological significance
Time of Start of Season (SOS)	Beginning of measurable photosynthesis
Time of End of the Season (EOS)	Cessation of measurable photosynthesis
Duration of Growing Season	Duration of photosynthetic activity
Time of Maximum Greenness	Time of maximum photosynthesis
NDVI at start of growing season	Level of photosynthetic activity at SOS
NDVI at end of growing season	Level of photosynthetic activity at EOS
Maximum NDVI	Maximum level of photosynthetic activity
Seasonally integrated NDVI	Photosynthetic activity in growing season
Rate of green-up	Acceleration of photosynthesis
Rate of senescence	Deceleration of photosynthesis

Table 1. NDVI-based phenological metrics and interpretation (After Reed et al. 1994)

Several other methods have been used to model the shapes of NDVI seasonal curves. For example, Zhang et al. (2003) using MODIS data stated that “vegetation phenology can be represented using series of piecewise logistics functions of time”. They suggested that, since the representation is general, it can be used for a description of the phenology of ecosystems characterized by complex behavior. This approach, however, requires a model for each major change in the shape of the NDVI curve which is impractical. Eastman and Fulk, (1993), used standardized principal components analysis (PCA) for analysis of change using spatial time series. They argue that the second to subsequent principal components correspond to change elements of successive decreasing magnitude.

de Beurs and Henebry (2004), demonstrated the use of quadratic models (i.e. parabolas) for assessing land cover change and phenology in semi-arid areas. Although this approach is promising, tropical areas may require more complex models since vegetation index curves of tropical areas exhibit shapes which do not follow a parabolic shape. Also classical Fourier methods have been used because they have been shown to be more sensitive to seasonal variability (Moody and Johnson 2001, Azzali and Menenti 2000, Olsson and Eklundh 1994) and they can be adapted to specific environments.

2.3.2 Annual Response of Humid and Sub-humid Tropical Vegetation

Remote sensing technology is the only way to monitor land cover changes over large areas particularly in tropical areas which are often isolated and inaccessible but recently have been experiencing high rates of deforestation due to human migration and expansion of the agricultural frontier (Sader et al. 1994). Sader and colleagues have

monitored rates and trends of forest clearing from the mid-1980's to 1990's using Landsat Thematic Mapper (TM) imagery in Guatemala. This type of work together with the Mexican forest inventories of 1990 and 2000 (Velazquez et al. 2000), and Conservation International efforts in Guatemala, can be used to help one understand long-term patterns of change. However, conventional approaches have generally used one date of Landsat TM data affordable for small areas, and are often carried out one every five to ten years.

Understanding cyclic variations is challenging because of the extreme complexity of tropical ecosystems, species diversity, and evolutionary history (Williams-Linera and Meave 2002). Another important issue in current tropical research is the process of succession represented by different stages of tropical secondary forests lands such as slash and burn cultivation and clearing to create pastures, sugar cane and coffee plantations (Williams-Linera and Meave 2002).

Although the use and value of satellite time-series data for monitoring vegetation seasonality has been established, there are only a limited number of methods for extracting seasonal parameters of metrics from such data Jonsson and Eklundh (2002). argued that most land cover types can be described by an annual cycle. However, tropical areas have different and less marked seasonal behavior compared with temperate areas. Satellite remote sensing systems having high temporal resolution but typically moderate or coarse spatial resolution, have increasingly been used to map, characterize and model the phenology (seasonality) of vegetation.

Vegetation indices are transformations of two or more spectral bands and are designed to enhance the vegetation properties response and allow spatial and temporal

inter-comparison of the photosynthetic activity and variations in the canopy structure (Huete 2002).

Following are two examples of a single year NDVI response in tropical humid and sub-humid areas. The first site corresponds to a tropical rain forest in the Montes Azules Biosphere reserve where there is rain all year round, increasing during the summer season. As can be seen in Figure 8, the NDVI response is very high. The profile is almost flat with relative low values between the months of February to May and November-December and very high values the rest of the year.

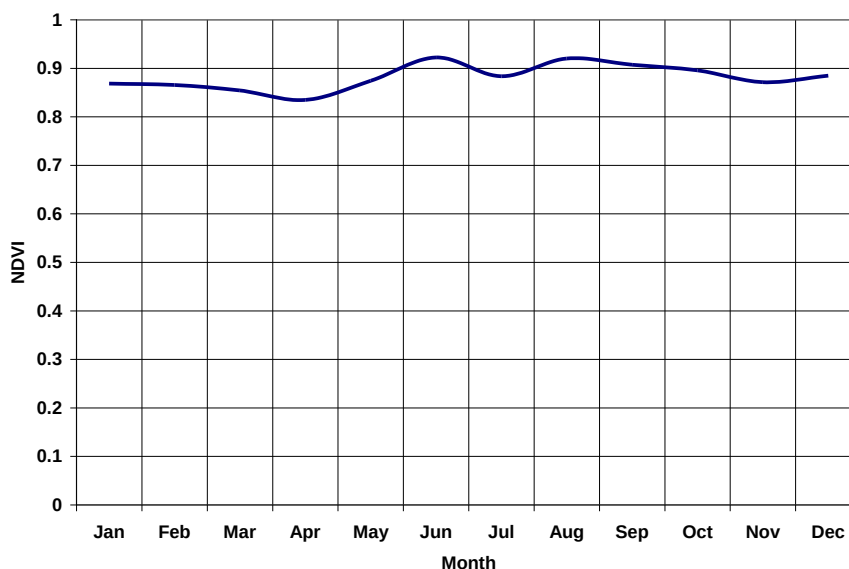


Figure 8. Single year tropical rain forest sample. Values of the NDVI are very high and show almost no variations throughout the year.

The other example corresponds to a tropical deciduous forest site (Figure 9), sampled in an area with strong dry/wet seasons. This type of vegetation loses almost all of its leaves during the dry period. The profile shows the shape common in areas with strong seasonality. However, it is interesting to see that even the minimum NDVI value is

relatively high (0.4). The length of the growing season extends from mid-March to mid-October, which is considerably long. There is also a bimodal NDVI distribution with a relative minimum at the end of July early August. This could be related to the mid-summer drought effect.

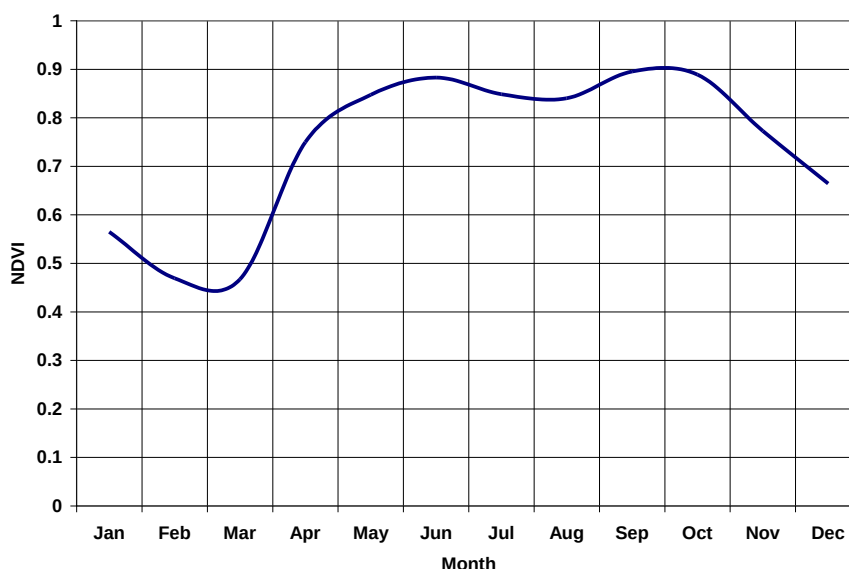


Figure 9. Single year, tropical deciduous forest sample. The NDVI values increase from the dry months to the wet months.

Cases like these two examples are common in tropical humid areas with very high NDVI values and bimodal distributions. These cannot be analyzed using the typical remote sensing phenology approaches.

2.3.3 Applying Remote Sensing Phenology to the Tropics

Human activity has drastically affected the ecosystems via habitat destruction and biodiversity reduction. Deforestation and habitat fragmentation in the tropics are issues of major concern that have numerous important consequences namely: the loss of natural

habitats and biodiversity, a negative impact on the global carbon cycle, loss of indigenous people's rights, species extinction and negative impact on climate. All of these consequences warrant better assessment of tropical land cover distribution and dynamics (Achard and Mayaux 2001).

The NDVI, has been reported to have a saturation problem under moderate to high biomass conditions which is the case of the tropical vegetation. Gitelson (2004), using crops as a reference, found that the NDVI remains invariant while LAI (Leaf Area Index) changes between 2 and 6. Wang et al. (2005), report that the NDVI reach its maximum for LAI near to 3 and greater. Despite of the lack of LAI estimations in tropical regions (only 8% of the total global LAI observations are from tropical biomes according to Asner et al. 2003), studies in tropical regions report an average of 8.2 in Central Africa (deWasseige et al. 2003), values ranging from 3.7 to 10.9 in Costa Rica (Kalbczka et al. 2004), Clark et al. (2008) report a total of 6.0 for all the plant functional groups in Costa Rica as well, 5.4 in tropical deciduous forest in Mexico (Mass et al. 1995) values which are higher than the limit where the NDVI saturates, therefore, indices which offer an alternative to the NDVI saturation problem under high biomass conditions must be tested in tropical areas together with methodologies which can also describe the differences between land use/land cover types and the intra and inter annual differences.

Classification of high temporal resolution data is an alternative for rapid assessment monitoring. MODIS data at 250m spatial resolution may provide significant advantages. These data can be used for continuous monitoring of tropical areas subjected to deforestation and other threats. The radiometric and geometric properties of the

MODIS sensor combined with improved atmospheric correction and cloud screening provided as MODIS final product (Zhang et al. 2003), substantially improve the basis to study vegetation monitoring applications using time series data by capturing the behavior of vegetation throughout the year.

References

- Achard, F., H. Eva, and P. Mayaux. 2001. Tropical forest mapping from coarse spatial resolution satellite data: production and accuracy assessment issues. *International Journal of Remote Sensing* 22:2741-2762.
- Allen, J.C. and D.F. Barnes. 1985. The Causes of Deforestation in Developing Countries. *Annals of the Association of American Geographers* 75(2):163-184.
- Asner, G.P., J.M.O. Scurlock, and A. Hicke. 2003. Global synthesis of leaf area index observations: implications for ecological and remote sensing studies. *Global Ecology and Biogeography* 12(3):191-205.
- Azzali, S. and M. Menenti. 2000. Mapping vegetation-soil-climate complexes in southern Africa using temporal Fourier analysis of NOAA-AVHRR NDVI data. *International Journal of Remote Sensing* 21(5):973-996.
- Bazzaz, F.A. and S.T.A.Pickett. 1980. Physiological Ecology of Tropical Succession: A Comparative Review. *Ann. Rev. Ecol. Syst* 11:287-310.
- Blanco-Jorge, L.A. and J.G. Garcia. 1997. A study of habitat fragmentation in Southeastern Brazil using remote sensing and geographic information systems (GIS). *Forest Ecology and Management* 98:35-47.
- Bradley, B.A., R.W. Jacob, J.F. Hermance, and J.F. Mustard. 2007. A curve fitting procedure to derive inter-annual phenologies from time series of noisy satellite NDVI data. *Remote Sensing of Environment* 106(2):137-145.
- Brown, S. and A.E. Lugo. 1990. Tropical Secondary Forests. *Journal of Tropical Ecology* 6(1):1-32.

- Chazdon, R.L.M.R.A. 2002. La adquisicion de carbono en las plantas. *In Ecologia y Conservacion de Bosques Neotropicales*, eds. M.R.Guariguata and G.H.Kattan. 225-50. Libro Universitario Regional: Costa Rica.
- Clark, D.B., P.C. Olivas, S.F. Oberbauer, D.A. Clark, and M.G. Ryan. 2008. First direct landscape-scale measurement of tropical rain forest Leaf Area Index, a key driver of global primary productivity. *Ecology Letters* 11(2):163-172.
- Curtis, S. and D.W. Gamble. 2008. Regional variations of the Caribbean mid-summer drought. *Theoretical and Applied Climatology* 94(1):25-34.
- de Beurs, K.M. and G.M. Henebry. 2004. Trend analysis of the Pathfinder AVHRR Land (PAL) NDVI data for the deserts of central Asia. *Geoscience and Remote Sensing Letters, IEEE* 1(4):282-286.
- de Beurs, K.M. and G.M. Henebry. 2005. A statistical framework for the analysis of long image time series. *International Journal of Remote Sensing* 26(8):1551-1573.
- de Wasseige, C., D. Bastin, and P. Defourny. 2003. Seasonal variation of tropical forest LAI based on field measurements in Central African Republic. *Agricultural and forest meteorology* 119(3-4):181-194.
- Eastman, R.J. and M. Fulk. 1993. Long Sequence Time Series Evaluation Using Standardized Principal Components. *Photogrammetric Engineering & Remote Sensing* 59(8):1307-1312.
- Echeverria, C., A.C. Newton, A. Lara, J.M.a.R. Benayas, and D.A. Coomes. 2007. Impacts of forest fragmentation on species composition and forest structure in the temperate landscape of southern Chile. *Global Ecology and Biogeography* 16(4):426-439.

- Gitelson, A.A. 2004. Wide Dynamic Range Vegetation Index for Remote Quantification of Biophysical Characteristics of Vegetation. *Journal of Plant Physiology* 161:165-173.
- Guariguata, M.R. and R. Ostertag. 2002. Sucesión Secundaria. In *Ecología y conservación de Bosques Neotropicales*, ed. M.R.K.G.H.Guariguata. 591-623. Libro Universitario Regional: Costa Rica.
- Hess, L., P. Ratana, A. Huete, C. Potter, and J. Melack. Use of MODIS enhanced vegetation index to detect seasonal patterns of leaf phenology in central Amazon várzea forest. Geoscience and Remote Sensing Symposium,2009 IEEE International,IGARSS 2009. Geoscience and Remote Sensing Symposium,2009 IEEE International,IGARSS 2009 4, IV-1007. 2009.
- Hoare, D. and P. Frost. 2004. Phenological description of natural vegetation in southern Africa using remotely-sensed vegetation data. *Applied vegetation Science* 7:19-28.
- Huete, A., K. Didan, T. Miura, E.P. Rodriguez, X. Gao, and L.G. Ferreira. 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment* 83:195-213.
- Huete, A.R., K. Didan, Y.E. Shimabukuro, P. Ratana, S.R. Saleska, L.R. Hutya, W. Yang, R.R. Nemani, and R. Myneni. 2006. Amazon rainforests green-up with sunlight in dry season. *Geophys. Res. Lett.* 33(6):L06405.
- Ichii, K., A. Kawabata, and Y. Yamaguchi. 2002. Global correlation analysis for NDVI and climatic variables and NDVI trends: 1982-1990. *International Journal of Remote Sensing* 23(18):3873-3878.

- Ichii, K., M. Maruyama, and Y. Yamaguchi. 2003. Multi-temporal analysis of deforestation in Rondonia state in Brazil using Landsat MSS, TM, ETM+ and NOAA AVHRR imagery and its relationship to changes in the local hydrological environment. *International Journal of Remote Sensing* 24(22):4467-4479.
- Ichii, K., H. Hashimoto, R. Nemani, and M. White. 2005. Modeling the interannual variability and trends in gross and net primary productivity of tropical forests from 1982 to 1999. *Global and Planetary Change* 48:274-286.
- Imbernon, J. and A. Branthomme. 2001. Characterization of landscape patterns of deforestation in tropical rain forests. *International Journal of Remote Sensing* 22(9):1753-1756.
- Jonsson, P. and L. Eklundh. 2002. Seasonality extraction by function fitting to time-series of satellite sensor data. *IEEE Transactions on Geoscience and Remote Sensing* 40(8):1824-1832.
- Kalbcaska, M., G.A. Sanchez-Azofeifa, B. Rivard, J.C. Calvo-Alvarado, A.R.P. Journet, J.P. Arroyo-Mora, and D. Ortiz-Ortiz. 2004. Leaf area index measurements in a tropical moist forest: A case study from Costa Rica. *Remote Sensing of Environment* 91(2):134-152.
- Kattan, G.H. 2002. Fragmentacion: patrones y mecanismos de extincion de especies. In *Ecologia y conservacion de Bosques Neotropicales*, ed. M.R.K.G.H.Guariguata. 561-90. Libro Universitario Regional: Costa Rica.
- Kobayashi, H. and D.G. Dye. 2005. Atmospheric conditions for monitoring the long-term vegetation dynamics in the Amazon using normalized difference vegetation index. *Remote Sensing of Environment* 97(4):519-525.

- Lambin, Eric F. 1999. Monitoring forest degradation in tropical regions by remote sensing: some methodological issues. *Global Ecology and Biogeography* 8:191-198.
- Laurance, W.F., S.G. Laurance, and P. Delamonica. 1998. Tropical forest fragmentation and greenhouse gas emissions. *Forest Ecology and Management* 110:173-180.
- Loveland, T. M., J. W. Merchant, D. O. Ohlen, and J. F. Brown. 1991. Development of a land cover characteristics data base for the conterminous US. *Photogrammetric Engineering & Remote Sensing* 57: 1453-63.
- Lucas, R.M., M.Honzak, P.J.Curran, G.M.Foody, and D.T.Nguele. 2000. Characterizing tropical forest regeneration in Cameroon using NOAA AVHRR data. *International Journal of Remote Sensing* 21(15):2831-2854.
- Mass J, J.M. Vose, W.T. Swank, and A. Martinez-Yrzar. 1995. Seasonal changes of leaf area index (LAI) in a tropical deciduous forest in west Mexico. *Forest Ecology and Management* 74 (1-3): 171-180.
- Moody, A. and D.M. Johnson. 2001. Land-Surface Phenologies from AVHRR Using the Discrete Fourier Transform. *Remote Sensing of Environment* 75(3):305-323.
- Muchoney, D., J. Borak, H. Chi, M. Friedl, S. Gopal, J. Hodges, N. Morrow, and A. Strahler. 2000. Application of the MODIS global supervised classification model to vegetation and land cover mapping of Central America. *International Journal of Remote Sensing* 21:1115-1138.
- Nelson, R.F., D.S. Kimes, W.A. Salas, and M. Routhier. 2000. Secondary Forest Age and Tropical Forest Biomass Estimation Using Thematic Mapper Imagery. *BioScience* 50(5):419-431.

- Nieuwolt, S. 1977. *Tropical Climatology An Introduction to the Climates of the Low Latitudes*. John Willey & Sons, Ltd.: United States of America.
- O'Brien Karen L. 1996. Tropical deforestation and climate change. *Progress in Physical Geography* 20(3):311-335.
- Olsson, L. and L. Eklundh. 1994. Fourier Series for analysis of temporal sequences of satellite sensor imagery. *International Journal of Remote Sensing* 15(18):3735-3741.
- Pennec, A., V.r. Gond, and D. Sabatier. 2011. Tropical forest phenology in French Guiana from MODIS time series. *Remote Sensing Letters* 2(4):337-345.
- Pettorelli, N., J.O. Vik, A. Mystereud, J.M. Gaillard, and C.J.a.S.N.C. Tucker. 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology and Evolution* 20(9):503-510.
- Reed, B.C., J.F. Brown, D. VanderZee, T.R. Loveland, J.W. Merchant, and D.O. Ohlen. 1994. Measuring phenological variability from satellite imagery. *Journal of Vegetation Science* 5:703-714.
- Reed, B. 2006. Trend Analysis of Time-Series Phenology of North America Derived from Satellite Data. *GIScience & Remote Sensing* 43(1):24-38.
- Sader, S.A., D.J. Hayes, D.E. Irwing, and S.S. Saatchi. 2001. Preliminary forest cover change estimates for central america (1990's) with reference to the proposed mesoamerican biological corridor. 2001 Annual Conference of the American Society of Photogrammetric Engineering and Remote Sensing, St. Louis, MO. Proceedings of the Year 2001 Annual Conference of the American Society of Photogrammetric Engineering and Remote Sensing.

- Scholes, R.J. and N. van Breemen. 1997. The effects of global change on tropical ecosystems. *Geoderma* 79:9-24.
- Schwartz, M.D., B.C. Reed, and M.A. White. 2003. Assessing Satellite-Derived start-of-season measures in the conterminous USA. *International Journal of Climatology* 22:1793-1805.
- Skole, D. and T. Compton. 1993. Tropical Deforestation and Habitat Fragmentation on the Amazon: Satellite Data from 1978 to 1988. *Science* 260:1905-1910.
- Stöckli, R., T. Rutishauser, D. Dragoni, J. O'Keefe, P.E. Thornton, M. Jolly, L. Lu, and A.S. Denning. 2008. Remote sensing data assimilation for a prognostic phenology model. *J. Geophys. Res.* 113(G4):G04021.
- Toumiso, H., A. Linna, and R. Kalliola. 1994. Use of digitally processed satellite images in studies of tropical rain forest vegetation. *International Journal of Remote Sensing* 15(8):1595-1610.
- Tucker, C.J. and J.R.G. Townshend. 2000. Strategies for monitoring tropical deforestation using satellite data. *International Journal of Remote Sensing* 21(6&7):1461-1471.
- Velazquez, A., J.F. Mas, J.L. Palacio-Prieto, and G. Bocco. 2000. Land Cover Mapping to Obtain a Current Profile of Deforestation in Mexico. *Unasylva* 210:8-13.
- Wang, J., P.M. Rich, and K.P. Price. 2003. Temporal responses of NDVI to precipitation and temperature in the central Great Plains, USA. *International Journal of Remote Sensing* 24(11):2345-2364.

- Williams-Linera, G. and J. Meave. 2002. Patrones Fenologicos. *In Ecologia y conservacion de bosques neotropicales*, eds. M.R.Guariguata and G.H.Kattan. 407-31. Libro Universitario Regional: Costa Rica.
- Wright S.Joseph and F.H. Cornejo. 1990. Seasonal drought and leaf fall in a tropical forest. *Ecology* 71(3):1165-1175.
- Zhang, X., M.A. Friedl, C.B. Schaaf, A.H. Strahler, J.C.F. Hodges, F. Gao, B.C. Reed, and A. Huete. 2003. Monitoring vegetation phenology using MODIS. *Remote Sensing of Environment* 84(3):471-475.

Chapter 3 Study area

3.1 The Neotropical Region

According to Hartshorn (2002), the tropical forests of Latin America and the Caribbean, are the most important in the world because of their geographic extent, biodiversity and ecological complexity. Of the ten countries with the largest area of tropical forests, six of them are located in the neotropics (Brazil, Peru, Colombia, Bolivia, México and Venezuela). The neotropical region extends in latitude from southern Mexico and south Florida down to southern Brazil and northern Argentina including the Caribbean Islands. Limits in latitude are defined not by the astronomical tropics (23.5° North and South) but by the intensity of the cold season and the amount of precipitation (Hartshorn 2002). Neotropical forests caught the attention of scientists long ago starting with Alexander Von Humbolt during his travel to Venezuela in 1799 (Samper 2002). Low-land humid forests are the most extensive of the neotropical region occupying most of the Amazonia basin and low-lands of Central America. Annual precipitation in these areas ranges from 1,500mm to 3,500mm.

Ecological studies during the first part of the twentieth century showed that human presence was not significantly influencing neotropical ecosystems. It was thought that human influence is eventually erased by the natural succession process (Brown and Lugo 1990). Recently, there has been new interest in the influence of human activities on tropical forest ecosystems. Ecological changes are now recognized to be consequences of both, natural or human perturbations or a combination of both (Guariguata and Ostertag 2002).

It is widely known that humid and rainy neotropical forests in Latin America have been affected by diverse human activities during the historical past (Garcia-Montiel 2002). Tropical areas have been greatly affected by changes in land cover at accelerated rates and these changes are closely linked to socioeconomic development and sustainability issues (Allen and Barnes 1985; Zhang et al. 2003).

This dissertation focuses on the Mayan forest (the larger green patch in Figure 6) which is the largest continuous expanse of tropical rainforest in the Americas after the Amazon. The Mayan forest is part of Mesoamerica, an area comprising the five southeastern states in Mexico (Campeche, Chiapas, Quintana Roo, Tabasco and Yucatan) and the seven Central American countries (Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua and Panama). This region shares a common biological and cultural heritage (Rodriguez and Asquith 2004). Serves as a terrestrial bridge between two biogeographic realms (Figure 1): The North American Nearctic and South and Central American and the Caribbean Neotropic and this geographical position contribute to its exceptionally high biodiversity. Mesoamerica is among the most biologically diverse regions on the planet. Occupying only one percent of the surface of the planet, this area encompasses between seven and ten percent of all known forms of life and seventeen percent of all terrestrial species. It is the second most important area for endemism and species diversity. In regards to species diversity, it ranks number one in the world for reptiles and number two for amphibians, birds, mammals and non-fish vertebrates. In terms of endemism, Mesoamerica has the highest number of endemic mammals and the second highest number of endemic amphibian, bird, reptilian and non-fish vertebrates (Rodriguez and Asquith 2004). Additionally, topography produces multiple

microclimates. Many of the mountain ridges are considered evolutionary islands. This region, is focus of many protection efforts as it is an area of particular ecological importance. It provides a significant opportunity to analyze the effects of land use change and forest degradation.

3.2 Occupation History

The region was occupied by the Mayan civilization starting one thousand and one hundred years ago and was subjected to intensive land use based on slash and burn agriculture (Rice 1984). Even today, the vegetation characteristics and patterns are influenced by the ancient Mayan agricultural practices (Hayes et al. 2002). For example, many areas are now late secondary rather than original forest (Brown and Lugo 1990). Furthermore, many traditional agriculture practices continue to survive to date (Gomez-Pompa and Kaus 1999). During the last twenty to thirty years, the forest has been subjected to extreme demographic and ecological pressures resulting in conversion of large areas of original tropical rain forest to shifting and/or permanent agriculture.

Approximately four hundred thousand hectares (4,000 Km²) of forest is destroyed every year. This fact makes the region one of the most endangered biodiversity hotspots in the world (Rodriguez and Asquith 2004).

After the Mayan collapse, survivors started a new cycle of growing population that lasted for 600 years until the Spanish arrival (Gomez-Pompa and Kaus 1999). For many centuries, the Mayans were able to maintain human populations in a tropical environment at numbers and densities higher than those found in the same place today (Gomez-Pompa and Kaus 1999). During the last twenty to thirty years, extensive areas of

original tropical forest have been converted to pasture and other agricultural activities. Immigration to the lowlands from the highlands of Guatemala and Chiapas has increased during this period as well (Wallace 1997).

Some anthropologists argue that the collapse of the Mayan culture can be attributed to several combined factors: population growth, political instability, warfare, overuse of resources, climate change and environmental destruction (Hayes et al. 2002). A similar combination of factors threatens the area today even though the current population is less than it was during the classical Mayan period. What happened several centuries ago could happen again in the present without sustainable management.

3.3 Study Area Location

The study area for this dissertation is a rectangle that extends from southeastern Mexico (west and central part of the States of Tabasco and Chiapas and the South of Campeche) to Northwest Guatemala (Department of Petén) Figure10. It extends from 89°10' W 15° 40' N to 93° 22' N 18°45' W. Covering an area of approximately 157,591 Km². The area was chosen to cover most of the continuous remnants of tropical rain forest and the Maya and Montes Azules biosphere reserves (among other protected areas). The site includes a wide variety of biophysical conditions including mountain ranges with transition vegetation and mixed, temperate, and isolated forests, and some micro climatic conditions suitable for tropical deciduous forests. Strong gradients of vegetation types are associated with temperature and precipitation conditions related to topography. Tropical deciduous forest occurs in some of the driest areas.

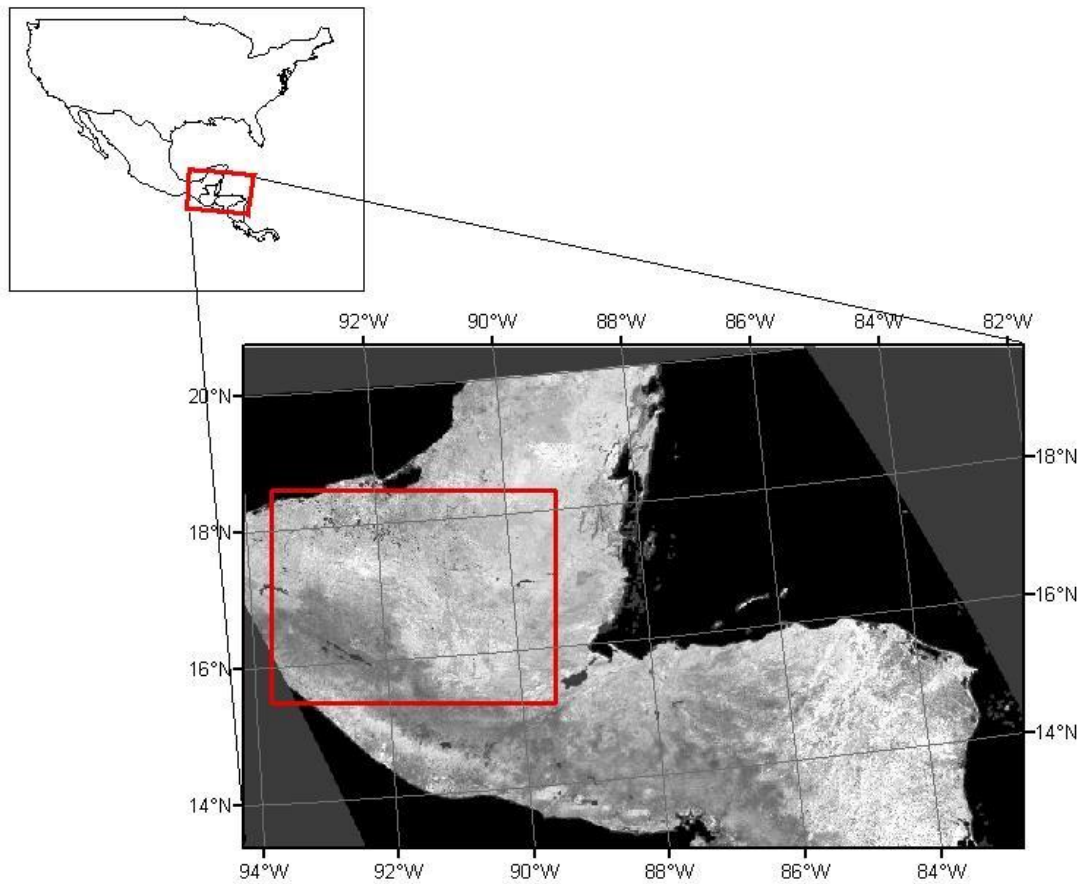


Figure10. The red square represents the extent of the study area plotted over a 16 day free cloud composite MODIS image. The inset show the location of the study area in North America

3.4 Topographic Regions

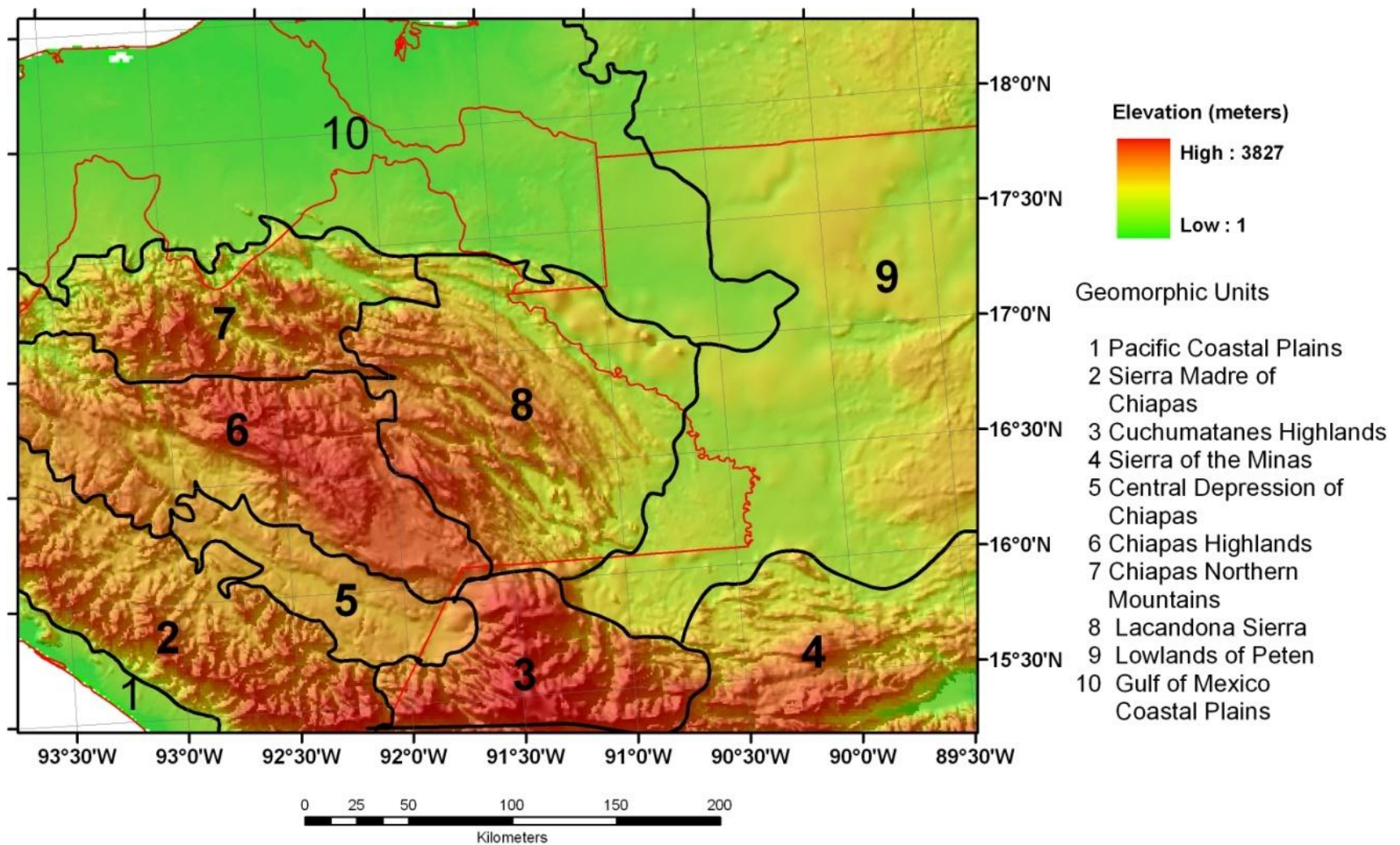
Topography plays a very important role in vegetation distribution (Figure 11). Major topographic features are oriented mainly in a NW-SE direction. From south to north, the major regions are:

1. The Pacific coastal plains formed by lowlands where tropical rainforest can be found, secondary vegetation in several stages of succession, tropical grasses resulting from the conversion of the original vegetation and wetlands.

2. The Sierra Madre de Chiapas ranges with elevations up to 3,000 m above the sea level including transition vegetation from tropical rain forests to mixed and temperate forests.
3. The Cuchumatanes Highlands in Guatemala are also a massive range of mountains with altitudes close to 3,000 meters above sea level and are covered by transition vegetation, mixed and temperate forest.
4. The previous region continues to the Sierra de las Minas with similar conditions.
5. Surrounded by mountain ranges (Sierra Madre, Chiapas Highlands and Cuchumatanes mountains, the central part of the Central Depression of Chiapas, is a depression where remnants of tropical deciduous forest can be found along with agriculture and pasture.
6. The Chiapas Highlands, located in the central part of the study area have altitudes close to 3,000 m and are covered by mixed and temperate forest along with annual crops.
7. The Northern and East mountains of Chiapas are formed by parallel mountain ranges covered by mixed and temperate forest, cloud forest, transition vegetation and tropical rain forest in the northern part.
8. Along the valleys, between the mountains, original vegetation has been intensively modified and remnants of tropical forest, secondary vegetation, annual crops and tropical grasses are found. In the Lacandona Sierra, the Montes Azules Biosphere reserve is located. The original vegetation along the valleys has also been modified. Secondary vegetation and remnants of tropical rain forest and tropical grasses are the current land cover.

9. The lowlands of Petén are covered by secondary vegetation, important remnants of tropical rain forest (the Maya biosphere reserve, is located here) but also secondary and tropical grasses that resulted from the modification of the original cover.
10. The Gulf of Mexico coastal plains are covered by remnants of tropical rain forest, secondary vegetation, tropical grasses and palm trees and wetlands close to the coast.

Figure 11. Elevation and Geomorphic Units of the study area. This map shows the complexity of the topography of the study area which influences the environmental condition.

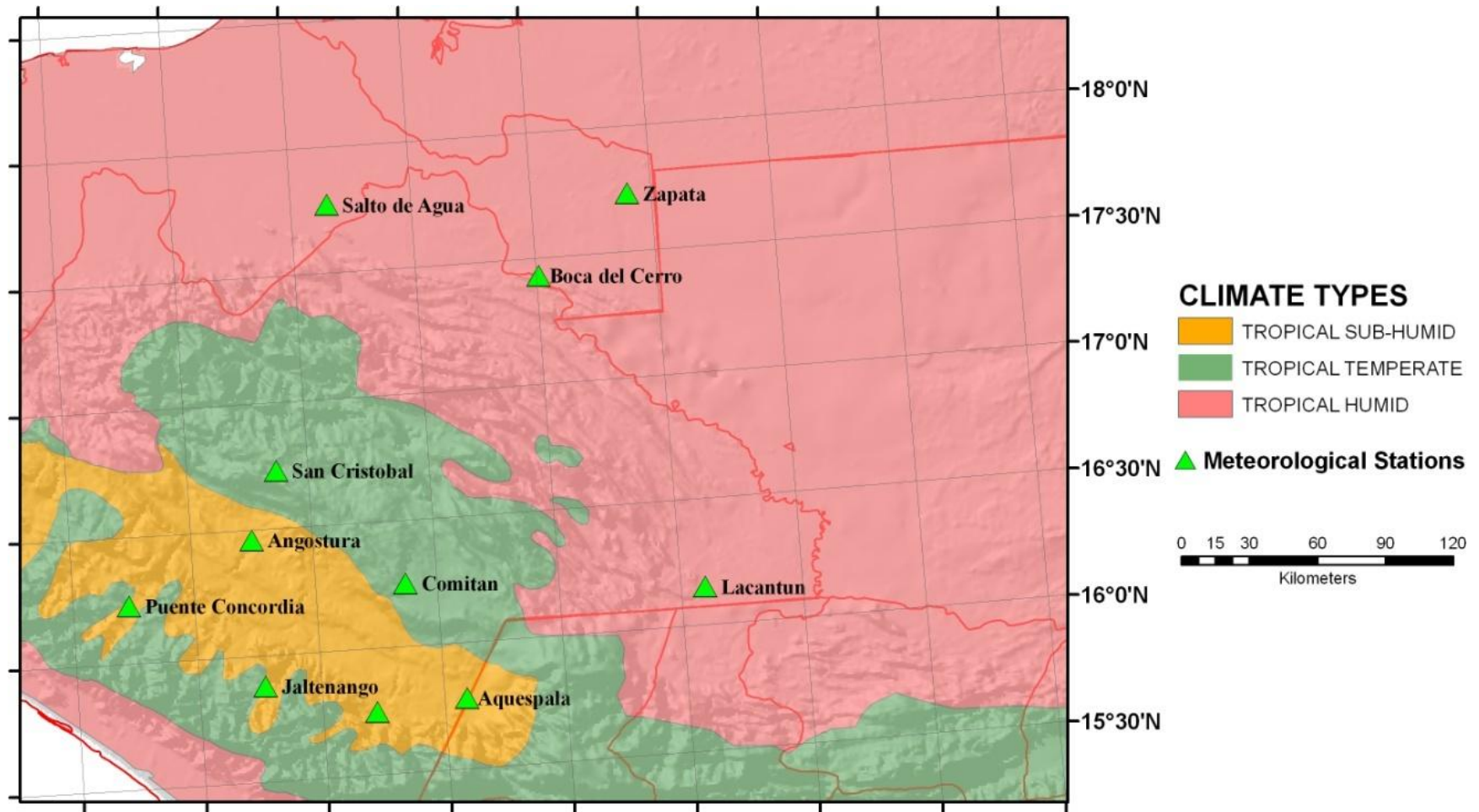


3.5 Climatic Characteristics

The climate of Mesoamerica is characterized by minor fluctuations in surface temperatures, and a well-defined rainy season during the months of May to October (Magaña et al. 1999). Precipitation is by far the most important meteorological element with high economic significance since most of the agricultural practices are rain-fed (Portig 1965). One particular characteristic of the rainy season over the central-southern part of Mexico and Central America is a bimodal distribution in precipitation, with maxima in June and September-October and a relative minimum during July-August (Magaña et al. 1999). This relative minimum in precipitation is known as midsummer drought (MSD) and locally called “*veranillo*” or “*canícula*”. This temporal precipitation behavior has been known for a long time but has never been explained (Magaña et al. 1999), nor has the vegetation response to it. However, since the success or failure of rain-fed areas depends on the behavior of the rainy season, it is expected that using satellite data could bring valuable information about the spatial response vegetation to the MSD.

For the purposes of this research, the study area was divided into three broad climatic zones shown in Figure 12: Tropical rainy or humid (warm temperatures and high levels of precipitation), tropical sub-humid (warm temperatures with a clear dry/wet season) and tropical temperate, (relative low temperatures with high levels of precipitation). The last two conditions result from topographic effects (height and rain shadow effects).

Figure 12. Broad climatic zones used in this work. Green triangles represent the meteorological stations. Temperate and sub-humid conditions are strongly influenced by the topography.



Examples of monthly averages of temperature and precipitation data from meteorological stations representatives of the climatic conditions are presented below (Figure 13 to Figure15). Figure 13 shows an example of the tropical humid conditions: warm temperatures throughout the year with a slight increase during the spring season and high volumes of precipitation increasing in the summer. The midsummer drought is characterized by a local minimum during the months of July-August whereas the *maxima* occur in the months of June and September.

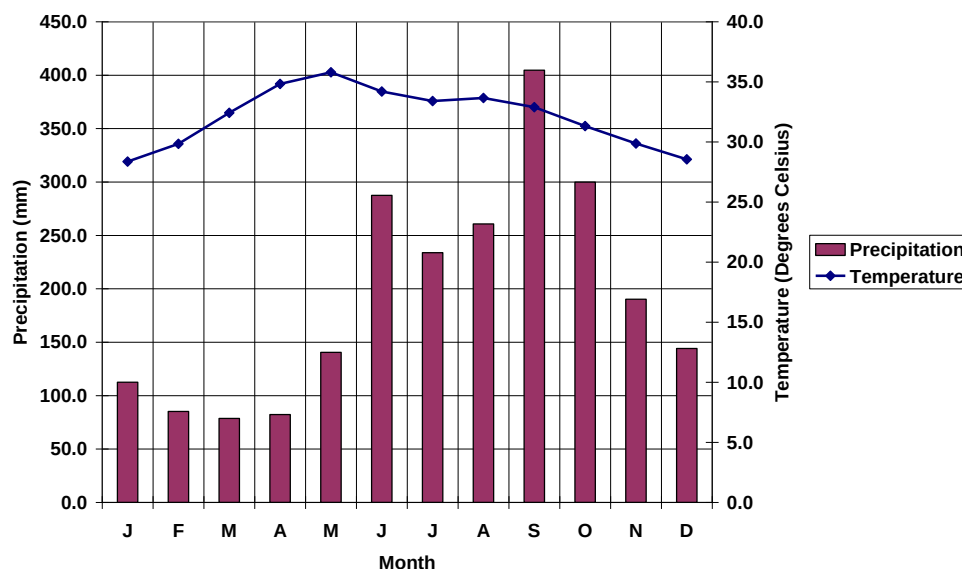


Figure 13. Tropical humid climograph (Boca del Cerro weather station). High mean temperatures uniformly distributed. High precipitation is more abundant during the summer

Figure 14, shows an example of the tropical sub-humid conditions with a clearly marked dry/wet season and very low precipitation during the dry season from November to April and a rainy season from May to October. The bimodal distribution which occurs in this region is evident with the two maxima values during the months of June and September. This climatic condition occurs in the Chiapas Central Depression which is surrounded and shadowed by The Sierra Madre de Chiapas, The Chiapas highlands and

Cuchumatanes Mountains (Geomorphic unit 9 in Figure 11). Temperature variations are less than 10 degrees Celsius throughout the year.

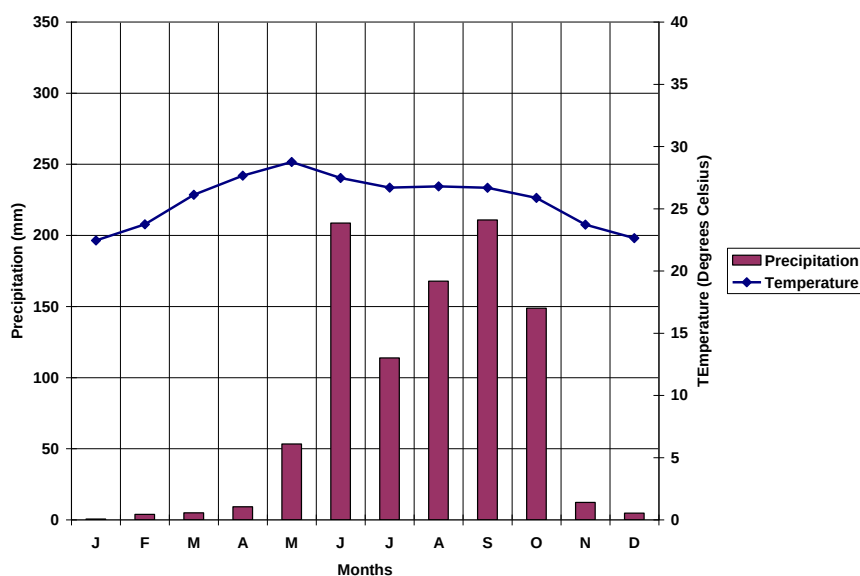


Figure 14. Tropical sub-humid climograph (Aquespala weather station). Located in an area surrounded by mountains which modifies the precipitation regime (strong dry/wet seasons) whereas the high temperatures are maintained throughout the year.

Temperate conditions (shown in Figure 15), are mainly located in the Chiapas highlands, middle and high parts of the Sierra Madre of Chiapas, north and east mountains and the Cuchumatanes and Sierra de las Minas mountains in Guatemala. Temperature ranges between 17-23°C. Precipitation shows a clear dry/wet season with most of the rain during the summer months showing a *maxima* during the months of June and September. The mid-summer drought effect can be seen by the low rainfall between June and September.

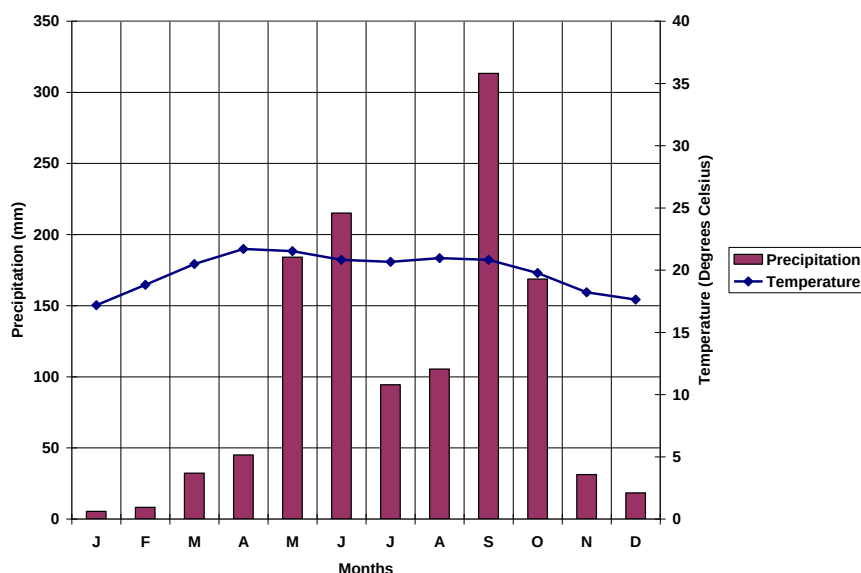
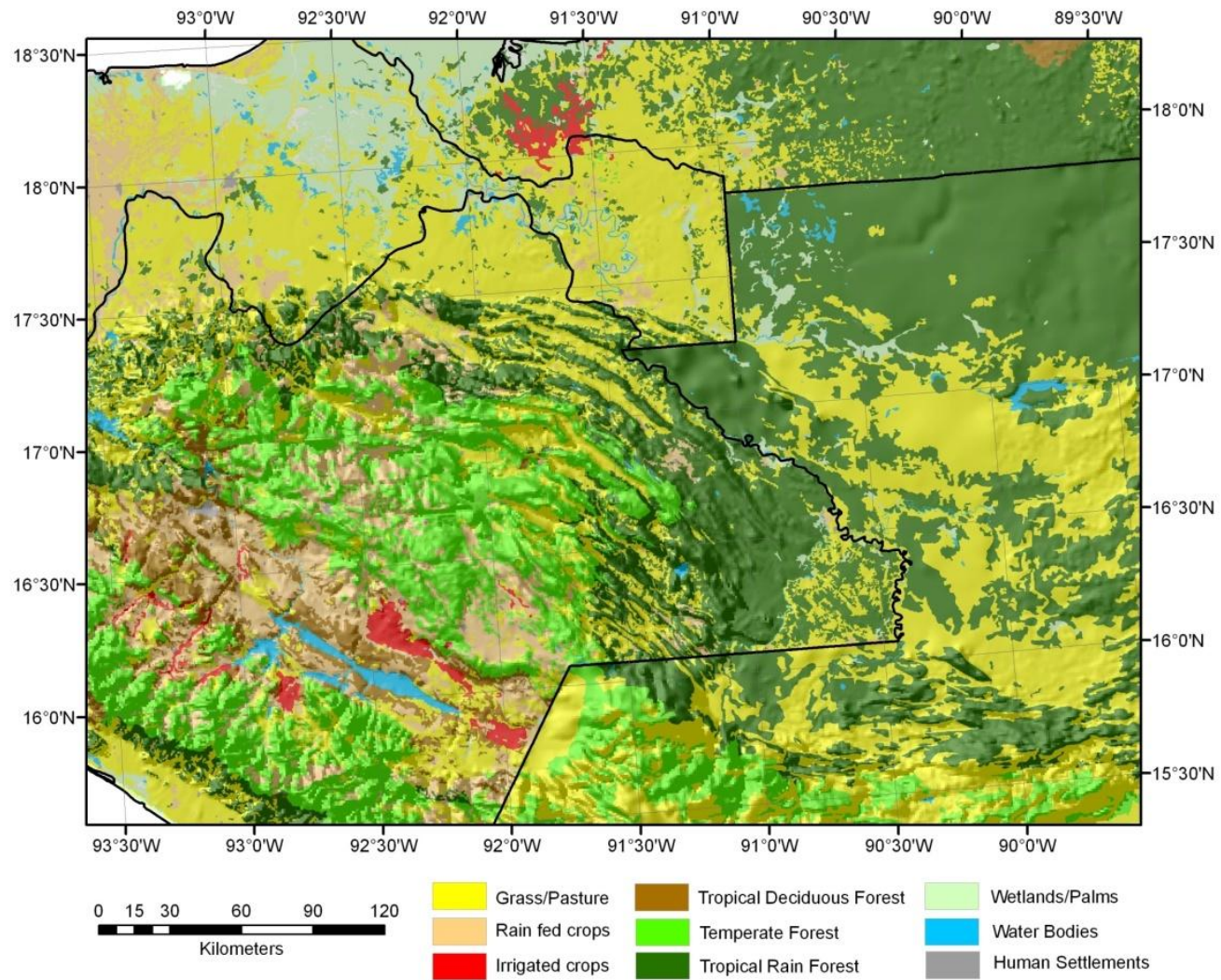


Figure15. Temperate conditions climograph. San Cristobal weather station. In temperate tropical regions the temperature is strongly modified by elevation resulting in lower values. The precipitation regime shows dry/wet conditions with the local minima values during the months of June and August.

3.6 Land cover/Land use

A land cover/land use map was developed using the 2000 national forest inventory of Mexico (Mas et al. 2000; Palacio-Prieto et al. 2000). Land use data for Central America were compiled by Conservation International for the year 2000. Classes were grouped into: grass/pasture, annual crops, irrigated crops, tropical deciduous forest, temperate forest, tropical rain forest, and wetlands/palms. A land use/land cover map is shown in Figure 16. As described above, topography is highly related to vegetation distribution. Tropical rain forest occupies lowlands, temperate and mixed forest are located in the highlands and mountain ranges, tropical deciduous forests are the central depression of Chiapas and wetlands lie close to the Gulf of Mexico coast. Annual crops and grasslands are found all over the area where the original vegetation has been modified.

Figure 16. Land use/ Land cover map showing the main classes. (Source: National Forest Inventory from Mexico and Conservation International data for Central America, circa 2000).



3.7 Protected Areas and the Mesoamerican Biological Corridor

Due to the biological importance of Mesoamerica and the high rates of deforestation, Mexico and Guatemala have established many protected areas with different statuses (biosphere reserves, national parks, natural reserves, etc). Together, these areas represent a network of natural protected areas forming the Mesoamerican biological corridor, a project that intends to create a network of biological corridors connecting isolated parks, reserves and forest fragments with the goal of providing an environment that yields a better prospect for long-term survival of the species (Welch et al. 2005).

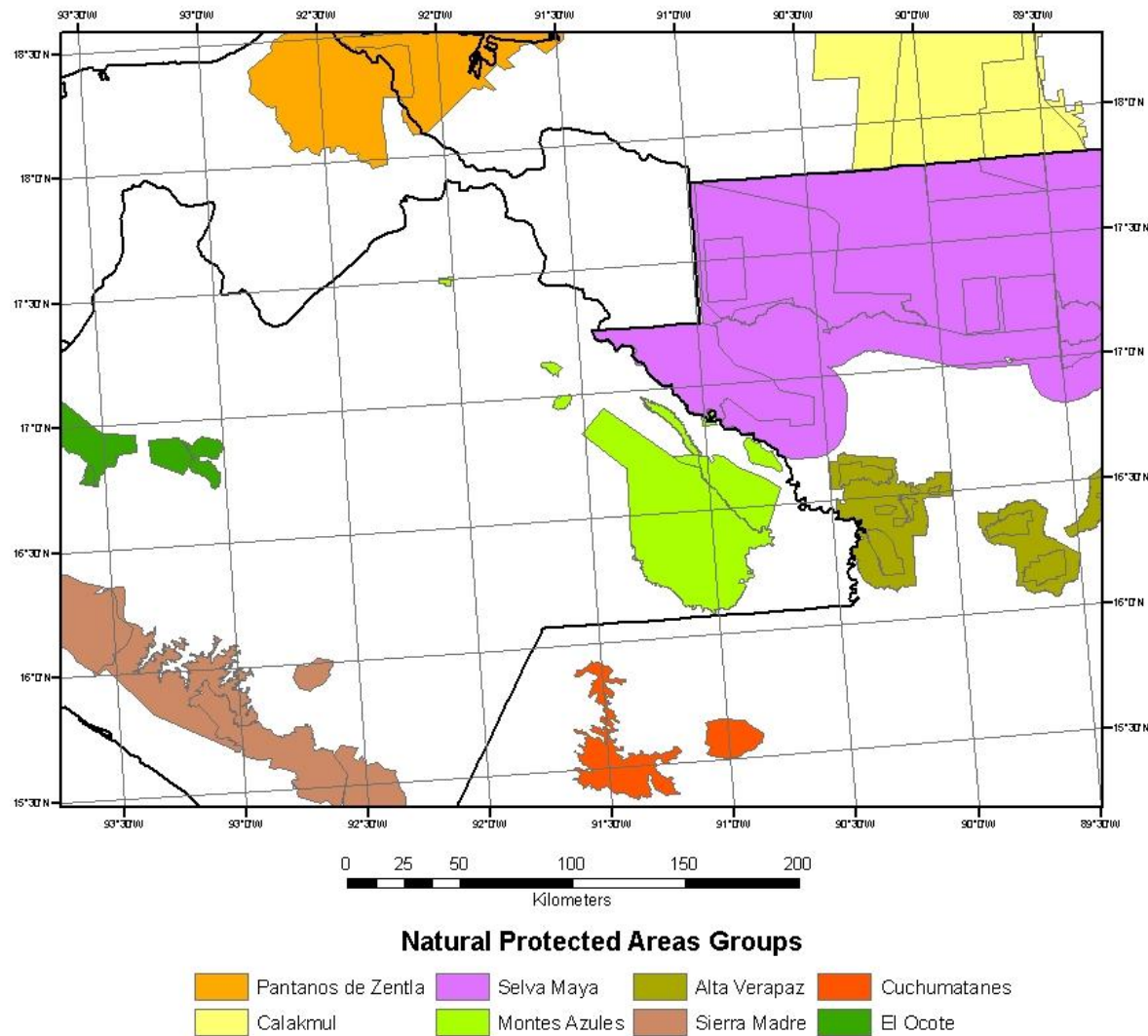
Guatemala's Maya Biosphere Reserve (MBR) established in 1990 represents the largest contiguous area of tropical forest remaining in Central America by far (Hayes et al. 2002) Located in Northern Peten, MBR covers 16,000 square kilometers of forest which is the core area. A buffer zone was also added at the southern edge of the reserve (Shriar 2002). Calakmul Biosphere Reserve on the Mexican side was declared in 1989 and is actually a continuation of the MBR located in the Mexican State of Campeche, covering 7,230 square kilometers and Montes Azules Biosphere reserve covering 3,312 square kilometers, making them the largest. Pantanos de Zentla in the Gulf Coast lowlands is an area occupied by wetlands.

For the purposes and scale of this research, protected areas were grouped according to location. The map in Figure 17, shows the groups of protected areas. The lines inside each group represent the limits of each protected area. The most important are: the Maya group which includes the polygons which define the Maya Biosphere reserve, the buffer zone and other areas such as the Laguna del Tigre Biotope, Mirador-

Rio Azul National Park, Yaxha-Naum-Naranjo Natural Monument and Tikal National Park among others. The Montes Azules group includes the Montes Azules and Lacantun Biosphere Reserves, Chankin Protected Area, Sierra de la Cojolita Community Reserve. The Sierra Madre group includes the La Sepultura and El Triunfo Biosphere reserves, and the Frailescana and Pico del Loro Ecological Conservation Areas. The Cuchumatanes group includes Sierra de los Cuchumatanes Special Protected Area and Visis Caba Biosphere Reserve. The Alta Verapaz Group includes several units called complexes, buffer zones, and wild refuges among others.

Detailed monitoring of the temporal characteristics of vegetation and land cover can help conservation and resource management efforts and rapid ecological assessment that support biodiversity, conservation management of protected areas and the development of the Mesoamerican Biodiversity Corridor

Figure 17. Natural protected areas. Protected areas are located in different environment conditions including tropical forests, cloud forests and wetlands among others.



References

- Allen, J.C. and D.F. Barnes. 1985. The Causes of Deforestation in Developing Countries. *Annals of the Association of American Geographers* 75(2):163-184.
- Brown, S. and A.E. Lugo. 1990. Tropical Secondary Forests. *Journal of Tropical Ecology* 6(1):1-32.
- Garcia-Montiel, D.C. 2002. El legado de la actividad humana en los bosques neotropicales contemporaneos. *In Ecologia y conservacion de Bosques Neotropicales*, eds. M.R.Guariguata and G.H.Kattan. 97-116. Libro Universitario Regional: Costa Rica.
- Gomez-Pompa, A. and A. Kaus. From pre-Hispanic to future conservation alternatives: Lessons from Mexico. *Preceedings of the National Academy of Sciences, USA* 96:5982-5986.
- Guariguata, M.R. and R. Ostertag. 2002. Sucesión Secundaria. *In Ecologia y conservacion de Bosques Neotropicales*, ed. M.R.K.G.H.Guariguata. 591-623. Libro Universitario Regional: Costa Rica.
- Harstshorn, G.S. 2002. Biogeografia de los bosques tropicales. *In Ecologia y conservacion de Bosques Neotropicales*, ed. M.R.K.G.H.Guariguata. 59-81. Libro Universitario Regional: Costa Rica.
- Hayes, D.J., S.A. Sader, and N.B. Schwartz. 2002. Analyzing a forest conversion history database to explore the spatial and temporal characteristics of land cover change in Guatemala's Maya Biosphere Reserve. *Landscape Ecology* 17:299-314.
- Magaña V., J.A. Amador, and S. Medina. 1999. The Midsummer Drought over Mexico and Central America. *American Meteorological Society* 12:1577-1588.

- Mas, J.F., A. Velazquez, J.L. Palacio-Prieto, and G. Bocco. 2000. Wall to Wall Land Use/Land Cover Mapping of Mexico: The National Forest Inventory 2000. *Photogrammetric Engineering & Remote Sensing* 68(10):966-968.
- Palacio-Prieto, J.L., G. Bocco, A. Velazquez, J.F. Mas, F. Takaki-Takaki, A. Victoria, L. Luna-Gonzalez, G. Gomez-Rodriguez, J. Lopez-Garcia, M. Palma, I. Trejo-Vazquez, A. Peralta-Higuera, J. Prado-Molina, A. Rodriguez-Aguilar, R. Mayorga-Saucedo, and F. Gonzalez Medrano. 2000. La condicion actual de los recursos forestales en Mexico: resultados del Inventario Forestal Nacional 2000. *Investigaciones Geograficas, Boletin del Instituto de Geografia, UNAM* 43:183-203.
- Portig, W.H. 1965. Central American Rainfall. *Geographical Review* 55(1):68-90.
- Rice, D.S. and P.M. Rice. 1984. Lessons from the Maya. *Latin American Research Review* 19(3):7-34.
- Rodriguez O, C. and N. Asquith. Critical Ecosystem Partnership Fund Ecosystem Profile Northern Region of the Mesoamerica Biodiversity Hotspot Belize, Guatemala, Mexico. C.Rodriguez O. and Asquith, N. 62.
- Samper, C. 2002. Presentacion. *In Ecologia y conservacion de bosques neotropicales*, 11-20. Libro Universitario Regional: Cartago, Costa Rica.
- Shriar, A.J. 2002. Food security and land use deforestation on northern Guatemala. *Food Policy* 27:395-414.
- Wallace D.R. 1997 Central American landscapes. In: Coates AG (ed) *Central America, a natural and cultural history*. Yale University Press, New Haven London,

- Welch, R.M., D.K. Ray, U.S. Nair, T. Sever, and D. Irwin. 2005. Impact of Deforestation on the Proposed Mesoamerican Biological Corridor in Central America. *19th Conf. on Hydrology, 85th AMS Annual Meeting, 9-13 Jan, 2005.*
- Zhang, X., M.A. Friedl, C.B. Schaaf, A.H. Strahler, J.C.F. Hodges, F. Gao, B.C. Reed, and A. Huete. 2003. Monitoring vegetation phenology using MODIS. *Remote Sensing of Environment* 84(3):471-475.

Chapter 4 Data and Methods

4.1 Data Sources

MODIS is an instrument carried aboard the Terra and Aqua satellites. The Terra satellite is known as the morning (AM) satellite while Aqua is known as the afternoon (PM) satellite. Terra MODIS and Aqua MODIS view the entire Earth's surface daily, acquiring data in thirty six spectral bands. The following table shows the primary use of each band number and the bandwidth for each spectral band.

Primary Use	Band	Bandwidth ¹
Land/Cloud/Aerosols Boundaries	1	620 - 670
	2	841 - 876
Land/Cloud/Aerosols Properties	3	459 - 479
	4	545 - 565
	5	1230 - 1250
	6	1628 - 1652
	7	2105 - 2155
Ocean Color/ Phytoplankton/ Biogeochemistry	8	405 - 420
	9	438 - 448
	10	483 - 493
	11	526 - 536
	12	546 - 556
	13	662 - 672
	14	673 - 683
	15	743 - 753
	16	862 - 877
Atmospheric Water Vapor	17	890 - 920
	18	931 - 941
	19	915 - 965
Primary Use	Band	Bandwidth ¹
Surface/Cloud Temperature	20	3.660 - 3.840
	21	3.929 - 3.989
	22	3.929 - 3.989

	23	4.020 - 4.080
Atmospheric Temperature	24	4.433 - 4.498
	25	4.482 - 4.549
Cirrus Clouds Water Vapor	26	1.360 - 1.390
	27	6.535 - 6.895
	28	7.175 - 7.475
Cloud Properties	29	8.400 - 8.700
Ozone	30	9.580 - 9.880
Surface/Cloud Temperature	31	10.780 - 11.280
	32	11.770 - 12.270
Cloud Top Altitude	33	13.185 - 13.485
	34	13.485 - 13.785
	35	13.785 - 14.085
	36	14.085 - 14.385
¹ Bands 1 to 19 are in nm; Bands 20 to 36 are in μm ² Spectral Radiance values are ($\text{W}/\text{m}^2 \cdot \mu\text{m}\cdot\text{sr}$) ³ SNR = Signal-to-noise ratio ⁴ NE(Δ)T = Noise-equivalent temperature difference Note: Performance goal is 30-40% better than required		

Table 2. MODIS Bands. (source: < <http://modis.gsfc.nasa.gov/about/specifications.php>>)

There are two MODIS vegetation indices. The standard Normalized Difference Vegetation Index (NDVI), which is referred to as the continuity index, provides data equivalent to the NOAA-AVHRR derived NDVI for which more than 20 years of global NDVI records are available. The MODIS Enhanced Vegetation Index (EVI) is designed to improve sensitivity to differences in vegetation from sparse to dense vegetation conditions (Huete et al. 2002; Xiao et al. 2005) details of the formulation of both indices are given below.

MODIS vegetation index products are designed to provide robust and enhanced vegetation sensitivity minimizing variations resulting from the atmosphere, instrument view, sun angles, clouds and inherent non-vegetation influences such as canopy background and litter (Huete et al. 2002).

4.2 Data Preprocessing

Data were acquired and downloaded from the EOS Data Gateway. The EOS Data Gateway is the main interface for all data available from NASA's Earth Observation System Data Information System (EOSDIS). MODIS #13 Terra (16 day maximum value composites), tile h09v07 vegetation indices data from 2001 to 2005 were downloaded.

Preprocessing of the data included: extraction of the NDVI and EVI datasets, reprojection from the original MODIS Integerized Sinusoidal Projection (ISIN) to a Lambert Conic Conformal projection, and subsetting and dividing by a scale factor of 10000 in order to obtain true vegetation index values. Finally the twenty three images were stacked in order to build the annual time series. Figure 18 shows the MODIS tile in the native Integerized Sinusoidal Projection and Figure 19 shows the file reprojected to the Lambert Conic Conformal Projection.

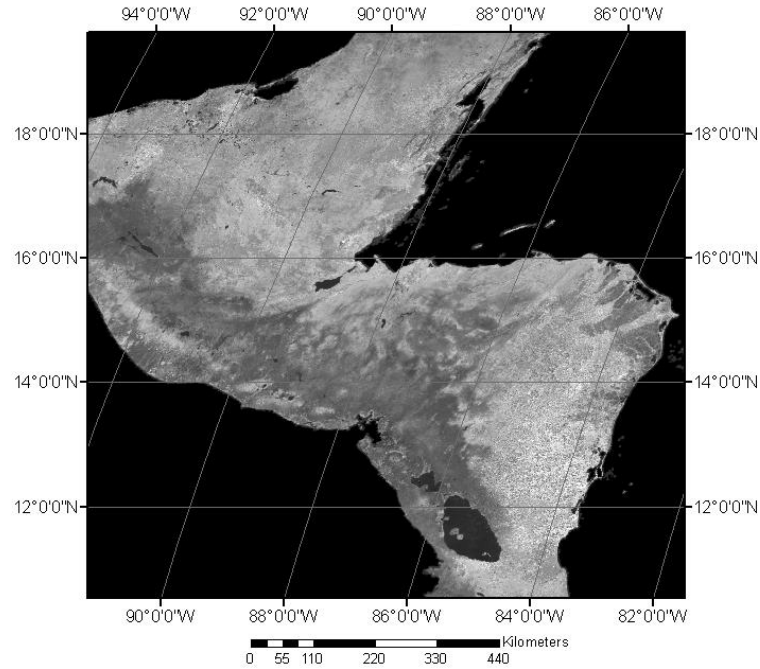


Figure 18. MODIS 16 day NDVI cloud free tile h09v07 which covers the study area in ISIN original projection. Darker tones represent less vegetation whereas whiter tones more abundant vegetation.

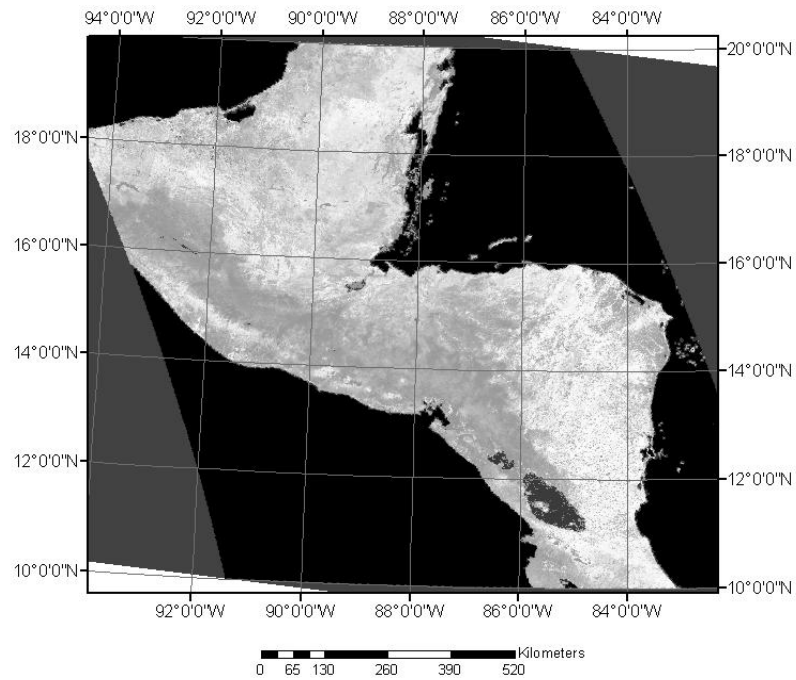


Figure 19. MODIS 16 day NDVI cloud free tile h09v07 which covers the study. Reprojected to a Lambert conical conformal projection. Darker tones represent less vegetation whereas whiter tones more abundant vegetation

4.3 Vegetation Indices

Coarse resolution satellite remote sensing has often been employed to characterize land cover using “greenness” indices (Eastman and Fulk 1993; Lu et al. 2003, Ichii et al. 2002; Hill and Donald 2003). Greenness indices are usually based on the contrast between the red and near-infrared portions of the electromagnetic spectrum, taking advantage of the spectral reflection/absorption characteristics of vegetation (Xiao et al. 2005; Pettorelli et al. 2005). Thus, greenness is generally related to plant productivity (Reed et al. 1994). The NDVI (Deering et al. 1975) is the most commonly used vegetation index; however, variations of this index (some of them using different or complementary bands to the red and NIR) have been proposed as a way to improve estimates of biophysical attributes such as leaf area index and the fractional vegetation coverage. In the case of the MODIS products, NDVI is called the continuity index because it can be used as a continuation of the AVHRR NDVI products used for more than twenty years.

The formula for the NDVI is the following:

$$NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}}$$

Equation 1. Normalized Difference Vegetation Index (NDVI)

Where:

ρ_{NIR} = NIR Reflectance

ρ_{Red} = Red Reflectance

The Enhanced Vegetation Index (EVI) was developed to optimize the vegetation signal improving sensitivity in high biomass areas. (Huete et al. 2002). This is done by correcting the reflectances for atmosphere and background influences. The equation for the EVI is the following:

$$EVI = G * \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + C_1 * \rho_{Red} - C_2 * \rho_{Blue} + L}$$

Equation 2. Enhanced Vegetation Index (EVI)

Where:

ρ_{NIR} = NIR Reflectance

ρ_{Red} = Red Reflectance

ρ_{Blue} = Blue Reflectance

C_1 = Atmosphere Resistance Red Correction Coefficient

C_2 = Atmosphere Resistance Blue Correction Coefficient

L = Canopy Background Brightness Correction Factor

G = Gain Factor

Recently, the Wide Dynamic Range Vegetation Index (WDRVI) (Gitelson 2004), has been proposed as a way to increase the range where the NDVI normally saturates.

$$WDRVI = \frac{\alpha * \rho_{NIR} - \rho_{Red}}{\alpha * \rho_{NIR} + \rho_{Red}}$$

Equation 3. Wide Dynamic Range Vegetation Index (WDRVI)

Where:

α = weighting coefficient

ρ_{NIR} = NIR Reflectance

ρ_{Red} = Red Reflectance

Note that when $\alpha = 1$, the equation yields the conventional NDVI formulation. With $\alpha < 1$, the contribution from the NIR channel is attenuated, making it more comparable to the red channel values. This is particularly important under conditions of moderate to high densities of green biomass, when NIR reflectance is significantly higher than that of the red reflectances (Viña et al. 2004).

WDRVI can be obtained from NDVI data by the inverse calculation according to the following formula: (Gitelson 2004).

$$WDRVI = \frac{\alpha + \alpha * NDVI + NDVI - 1}{\alpha + \alpha * NDVI - NDVI + 1}$$

Equation 4. WDRVI from NDVI

Given the variety of available indices, different resolutions and the complexity of tropical areas, sensitivity analysis is required in order to understand how the indices are related and to assess their strengths and weaknesses as analysis tools in tropical areas.

4.4 Multitemporal Maximum Vegetation Indices Composites

The construction of temporal profiles requires a procedure where several vegetation index images are sampled and composited over a given period of time (typically 10 to 16 days) are merged to produce a single cloud-free image. The most common algorithm used to generate composites is the maximum value composite (MVC) technique commonly used with the NOAA AVHRR-NDVI products (Swets et al. 1999). This procedure consists of selection, on a pixel by pixel basis, the highest NDVI value as

output to form the composite product during a given period of time. This method minimizes the selection of cloudy and contaminated aerosol pixels.

The MODIS vegetation index algorithm is built on a per-pixel basis over the multiple 16-day observation periods to generate a composite vegetation index. Data are filtered based on quality, cloud and viewing geometry and only the higher quality pixels are selected for compositing (Huete et al. 2002). The vegetation index product is designed to provide consistent spatial and temporal comparisons of global vegetation condition which can be used to monitor vegetation activity such as phenology, change detection and biophysical interpretations.

As was discussed previously, NDVI composites have been used as a vegetation monitoring tool. Composites are utilized to construct temporal profiles of vegetation activity enabling intra and inter-annual comparisons of these profiles. During the past two decades it has become common to use time sequences of biweekly maximum value from AVHRR NDVI composites accumulated over a year (or sometimes several years) for modeling seasonal variation. These sequences have been used to relate variations to phenological variables. (Foody and Boyd 2003; Foody and Curran 1994; Achard and Blasco 1990). For each pixel a “greenness curve” is derived. In order to reduce factors that might be attributed to sensor or atmospheric anomalies, curves are often subjected to smoothing. Fluctuations in the “smoothed” greenness are assumed to reflect the seasonal state and behavior of land cover (Reed et al. 1994; Schwartz et al. 2003). In this research, smoothing was not applied to the data because the estimated values resulting from the Fourier series approximation method (which will be discussed later in detail) are smoothed.

4.5 Analysis Procedures

4.5.1 Indices Comparison

The comparison between the NDVI, EVI and WDRVI was done by statistical correlation with precipitation data, wavelets analysis and sensitivity analysis. The data used for this comparison were drawn from samples from regions of interest (ROI's) using Landsat ETM imagery. Landsat imagery was used due its higher spatial resolution which helps to identify and delineate the land cover types such as tropical rain forest, annual crops, tropical deciduous forest, secondary forest, temperate forest, grass and pasture. The temporal behavior of each index for the different land cover types was assessed by plotting profiles which describe the index value through time. In order to observe relationships between pairs of indices, scatter plots were used. Also, in order to search for relationships between pairs of indices, plotting between pairs and triplets was performed. Linear trends were adjusted in order to yield the R^2 value. The non-linear equation resulting from the relationship between indices was later used for sensitivity analysis.

Once the relationship between both indices is known, a sensitivity index can be calculated as proposed by Viña et al. (2004) using the following formula (NDVI vs WDRVI case):

$$Sr = (\partial WDRVI / \partial NDVI) * (\Delta NDVI / \Delta WDRVI)$$

Equation 5. Relative sensitivity equation

Where:

$\partial WDRVI / \partial NDVI$ is the first derivative of the function WDRVI vs NDVI and
 $\Delta NDVI / \Delta WDRVI$ are the indices ranges.

Values of $Sr < 1$ indicate situations where the NDVI is more sensitive than the WDRVI and vice versa.

Another way to detect which of the indices has or better reflects the seasonal behavior is using a wavelet analysis. Wavelet analysis is becoming a common tool for analyzing local variations in time series. One case in particular is the temporal analysis of drought events related to ENSO (Mendoza et al. 2007) or temporal analysis of the Caribbean mid-summer drought (Curtis and Gamble 2008).

4.5.2 Modeling Land cover Seasonality of Tropical Regions

Vegetation index profiles of tropical vegetation cover types have different and complex shapes when compared with mid-latitude vegetation. Since the response of vegetation follows precipitation regimes, tropical vegetation response cannot be simplified like boreal vegetation where temperature is the main driving force. For example, in boreal forests, annual profiles can be simplified using accumulated growing degree-days (de Beurs, and Henebry 2005).

In this work, I analyzed complete annual profiles rather than partial profiles so that it was possible to simplify complex land cover profiles into a simpler mathematical function which expresses their behavior. Temporal profiles provide a basis for discriminating between land cover classes based on their phenology or seasonal variations. I analyzed the VI's profiles using a temporal feature extraction known as Fourier Series Approximation (Olsson and Eklundh 1994; Moody and Johnson 2001; Jakubauskas et al. 2001). The method is a mathematical procedure that breaks up a function into the frequencies that compose it in the same way that a prism breaks up light into colors (Burke Hubbard 1998). Fourier analysis has often been applied in remote sensing studies for phenology characterization (see Olsson and Eklundh 1994;

Jakubauskas et al. 2001; Moody and Johnson 2001; Jakubauskas et al. 2002. Olsson and Ekhlund (1994) used this method to characterize mono-modal and bi-modal behavior of NDVI over Africa. Jakubauskas et al. (2001) and Jakubauskas et al. (2002) applied the method to AVHRR data for crop identification in Finney County, Kansas using different temporal patterns of different crops (i.e. winter wheat versus corn).

The Fourier Method has been found to be an objective method that summarizes the temporal signatures that are sensitive to systematic changes in vegetation but relatively insensitive to nonsystematic data noise (Moody and Johnson 2001). Higher order harmonics of the Fourier decomposition may capture the phenology of secondary vegetation components or rapid surface changes associated with events such as fire, deforestation and flooding. This method can handle any shape of curves derived from vegetation profiles. The modeling relies on the description of the main components of the whole curve (optimal parameters) rather than specific break points related to the start/end, maximum/minimum of the season values. Therefore any kind of vegetation profile can be modeled, not only the ones that exhibit a clear seasonality. The mathematical function also is a smoother. Smoothing the profile eliminates spurious data. The Fourier coefficients which are related to the contribution of the trigonometric functions at each cycle simplified as amplitude and phases of the vegetation profiles were used to evaluate changes comparing the same parameter value between years. Also the set of Fourier coefficients were used to perform a land cover classification.

The Fourier series of a function is written:

$$y(e) = a_0 + \sum_{k=1}^k \left[c_k \cos\left(\frac{2\pi kt}{T}\right) \right] + \sum_{k=1}^k \left[s_k \sin\left(\frac{2\pi kt}{T}\right) \right]$$

Equation 6. Fourier series approximation equation

Where:

a_0 , c_k , s_k are the Fourier coefficients

k = number of cycles

t = time steps

T = total time

The Fourier series method is a way to represent any periodic function as a sum of sines and cosines (Burke-Hubbard 1998). Multiplying the trigonometric functions by coefficients, it is possible to change their amplitude (height of the curve); shifting the phase angle (time), results in a smoothed curve of the original data. Figure 20 shows the two period (second harmonic), three (third harmonic) and four period (fourth harmonic) sine function cases.

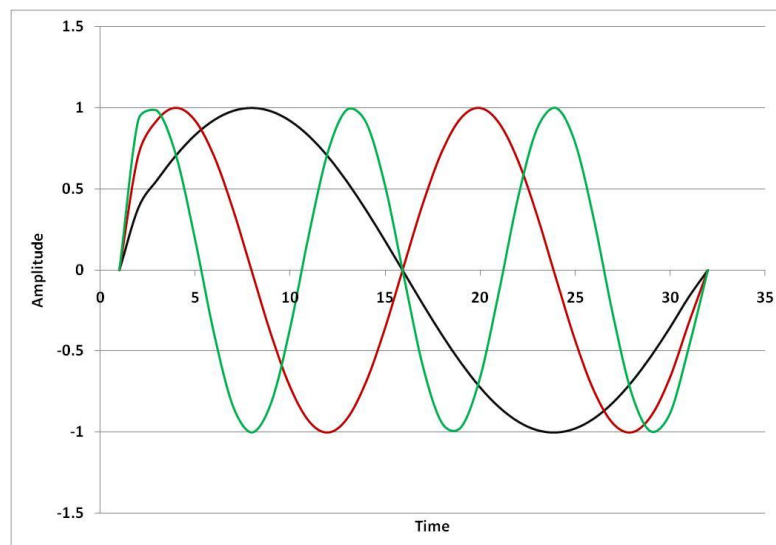


Figure 20. Sine functions for one, two and three periods. As the number of periods increase more complete cycles are for the same period of time.

Each Fourier term defines the number of complete periods (trigonometric functions) completed by a wave over a defined interval. Figure 21 shows the sum of the four harmonics.

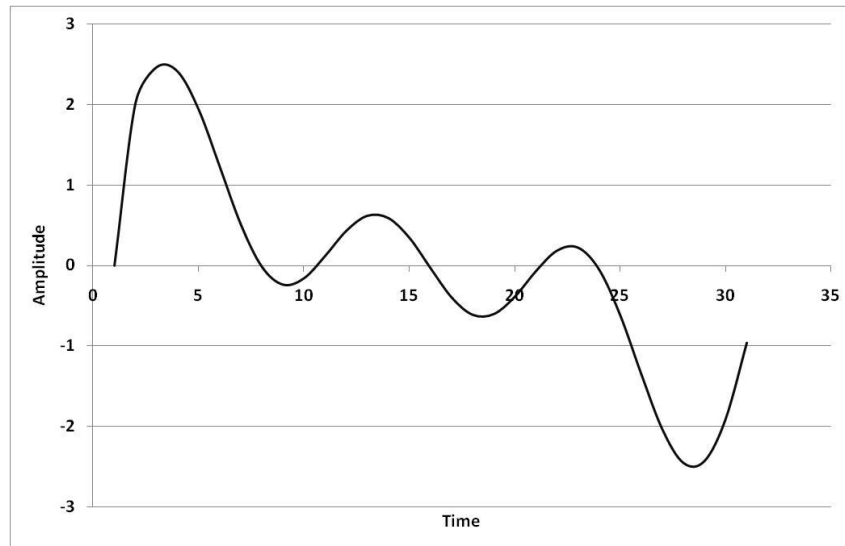


Figure 21. Sum of three sine functions. As time increases, the added function effect is less important.

Depending on the number of periods chosen, pairs of functions are required for each period. The expected value for each time step is calculated. An error measurement, such as the sum of squares (SSQ), must be minimized in order to obtain the optimal set of parameters which best fit that particular profile. Iterating by increasing the number of periods of the Fourier transformation, the fit to the original data series gets closer and fine variations can be observed. Figure 22 shows the fitting with one and two period (harmonics) and Figure 23, shows the fitting for four and six periods or harmonics.

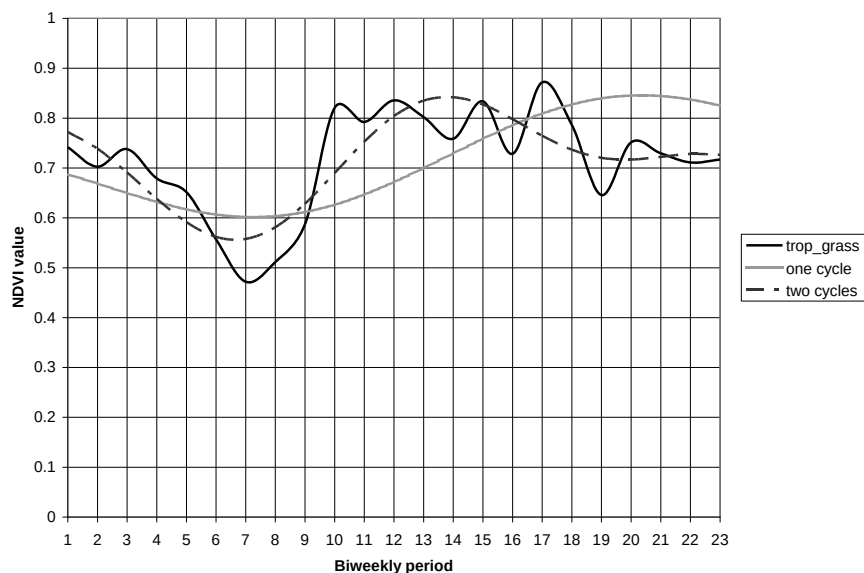


Figure 22 Fourier series approximations fitting (one and two cycles). The first period or cycle defines the overall shape of the original function, the two period case adjust with more detail to the original data.

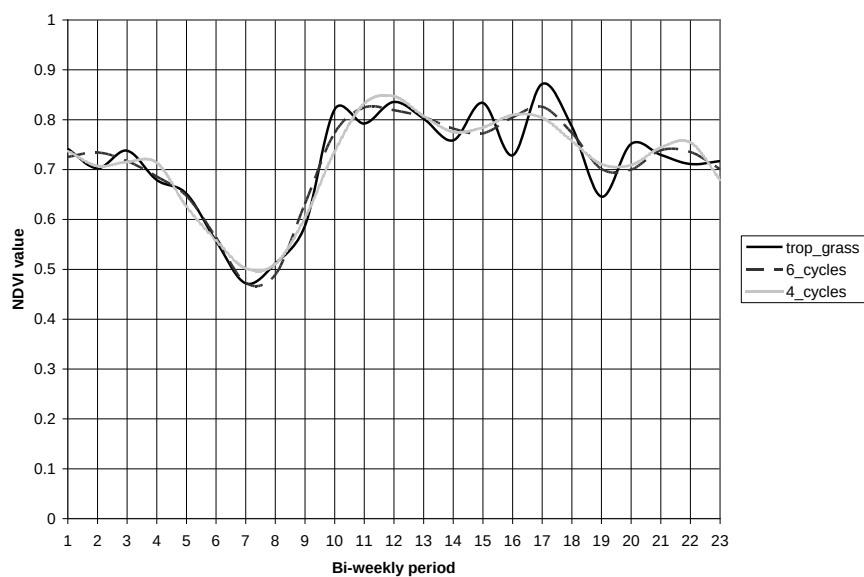


Figure 23. Fourier series approximation fitting (four and six cycles). As the number of periods is increased the adjustment to the original function is closer.

By increasing the number of sinusoids, the sum becomes more complex and real world cases are approximated with more accuracy. The following table shows the approximation using the sum of squares as an accuracy measure.

NUMBER OF PERIODS	SUM OF SQUARES
1	0.2429
2	0.0775
3	0.0655
4	0.0367
6	0.0268

Table 3. Sum of squares values. As the number of periods increase, the value of the sum of squares decrease which means a better adjust between the model and the data.

Once the best fit of the function according to the number of seasonal cycles for each profile is found, the extraction of the main features of the data can be done by analyzing the contribution of each parameter to the curve or by calculating extreme values (maximum and minimum peaks). Models will be applied pixel by pixel to the whole study area, thus obtaining spatial patterns of seasonal variations. Comparisons between years can then be made.

Using Equation 6, each component is comprised of sine and cosine waves of equal integer frequency. These two waves can be combined into a single cosine wave which has a characteristic amplitude and phase angle of the wave. The amplitude is the size and the phase angle is the offset of the wave.

According to Jakubauskas et al. (2001), the amplitude and phase angle of the function can be obtained by the following equation:

$$y(e) = a_0 + \sum_{k=1}^k c_k \cos\left(\frac{2\pi kt}{T} - \phi_k\right)$$

Equation 7. Fourier series equation (simplified)

Where:

c_k is the amplitude of the k th term (which is the k th harmonic) and ϕ_k is the phase angle of the k th term.

Depending of the shape of each particular curve there are specific constant, amplitude and phase values for each harmonic which can be used to differentiate or compare curves with different shapes.

Each vegetation index profile is related to a specific land cover type and is defined by a unique amplitude and phase angle for each harmonic component (Jakubauskas et al. 2001). Where the amplitude value is half of the height of a wave of the harmonic for each component and the phase angle is the offset between the origin and the peak of the wave (sine or cosine function) over the range 0 to 2π .

The amplitude and phase angle values can be also obtained from the Fourier coefficients obtained from Equation 6. The amplitude is a function of the square root of the sum of the squared coefficients c and s and the phase angle is the arc tangent of the quotient between the Fourier coefficients c and s for each harmonic.

Two examples of the amplitude and phase angle functions and values using four harmonics for two contrasting land cover types: tropical rain forest and tropical deciduous forest are shown in Figure 24, Figure 25 and Table 4. Phase angle values were converted to time (16-day period values).

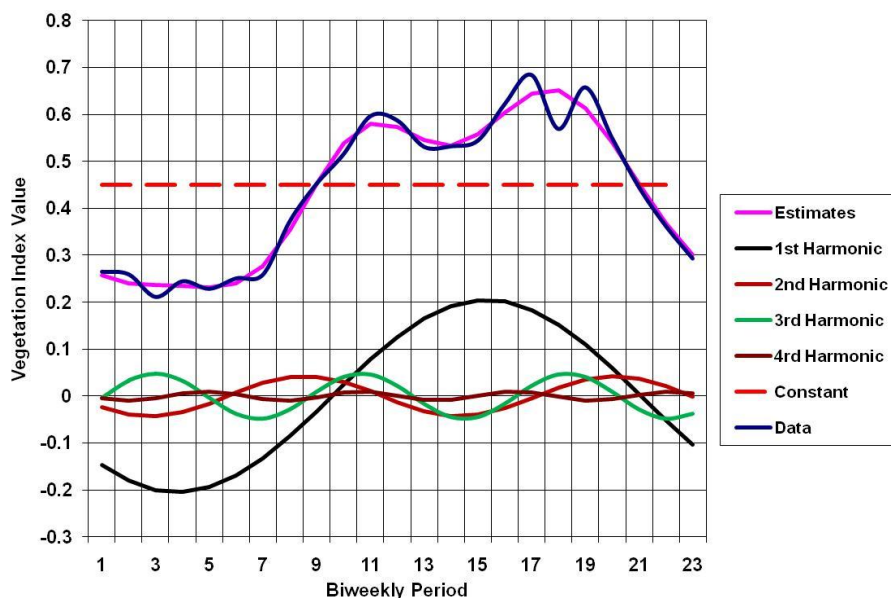


Figure 24. Comparison between the data, the estimated values and harmonics decomposition (Tropical Deciduous Forest site). Due to the nature of the data (strong dry/wet conditions) the first harmonic is high. As the number of harmonics increase the resulting functions are flatter and flatter showing local variations of the data.

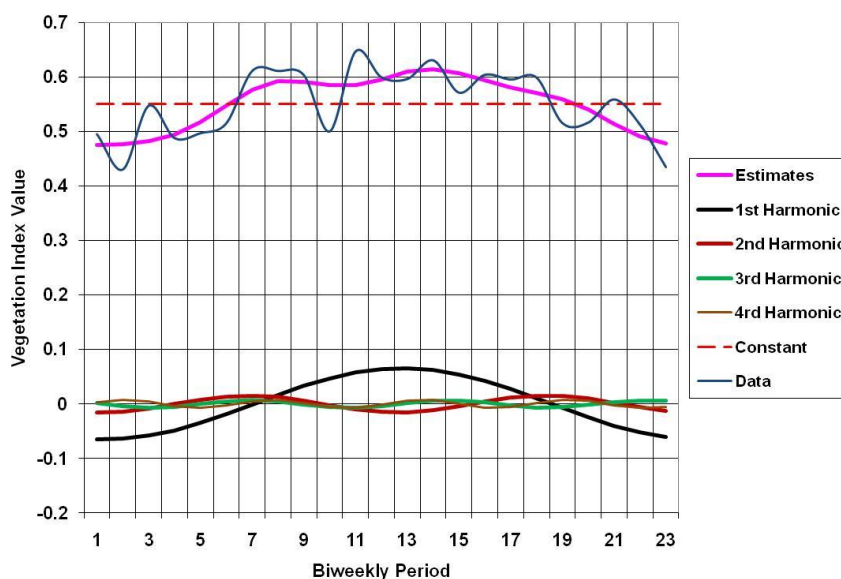


Figure 25. Comparison between the data, the estimated values and harmonic decomposition (tropical rainforest site). Since the data shows no seasonal behavior, the resulting functions are flatter compared with the tropical deciduous forest case. Lower harmonics shows local variations of the data.

FOURIER PARAMETER	TROPICAL DECIDUOUS FOREST	TROPICAL RAIN FOREST
Constant (a_0)	0.435	0.551
Amplitude 1 st	0.204	0.065
Amplitude 2 nd	0.042	0.015
Amplitude 3 rd	0.047	0.006
Amplitude 4 rd	0.009	0.007
Phase 1 st	15.317	12.814
Phase 2 nd	8.576	6.878
Phase 3 rd	2.997	3.092
Phase 4 rd	-0.8521	-0.80471

Table 4. Amplitude and phase angle Fourier coefficients for tropical deciduous and tropical rain forests. Except for the constant value which is higher for the tropical rain forest (higher overall values), the amplitude values are higher for the tropical deciduous forest which means more variations.

Constant Fourier coefficient (a_0) corresponds to the mean value of the decomposition. In the case of vegetation index profiles, the constant Fourier coefficient is assumed to indicate the overall productivity of the region for that time period. Therefore, it allows the valuable comparison of more and less productive areas as well as differences in productivity through time. The amplitude value of the first harmonic is used as an indicator of the variability of the productivity over time while phase value indicates timing.

Thus land cover with clear seasonality shows higher amplitude values mainly in the first two harmonics compared with a land cover with a more flat profile present where there are fewer seasonal variations. Phase values are related to the time of the peak value, therefore this can be used to look for shifting in the time of the peak when comparing different years. Similar land cover types have similar Fourier coefficients and therefore they were used to obtain an annual land cover classification based on seasonal properties

on a pixel basis. Also, Fourier coefficients were used to evaluate land cover changes by comparing each value for pairs of years. The use of Fourier analysis to analyze vegetation phenology is on one hand, a data reduction process and on the other hand a summarization of the temporal signature of the vegetation index profile which is sensitive to changes in vegetation (Moody and Johnson 2001).

References

- Achard, F. and F. Blasco. 1990. Analysis of Vegetation Seasonal Evolution and Mapping of Forest Cover in West Africa with the Use of NOAA AVHRR HRPT Data. *Photogrammetric Engineering & Remote Sensing* 10:1359-1365.
- Burke-Hubbard, B. 1996. *The world according to wavelets: the story of a mathematical technique in the making*. A. K. Peters, Ltd..
- Curtis, S. and D.W. Gamble. 2008. Regional variations of the Caribbean mid-summer drought. *Theoretical and Applied Climatology* 94(1):25-34.
- deBeurs, K.M. and G.M. Henebry. 2005. A statistical framework for the analysis of long image time series. *International Journal of Remote Sensing* 26(8):1551-1573.
- Deering, D.W., J.W. Rouse, R.H. Haas, and J.A. Schell. Measuring "Forage production" of grazing units from Landsat MSS data. Proceedings of the 10th International Symposium on Remote Sensing of Environment, 1169-1178. 1975.
- Eastman, R.J. and M. Fulk. 1993. Long Sequence Time Series Evaluation Using Standardized Principal Components. *Photogrammetric Engineering & Remote Sensing* 59(8):1307-1312.
- Foody, G.M. and P.J. Curran. 1994. Estimation of tropical forest extent and regenerative stage using remotely sensed data. *Journal of Biogeography* 21:223-244.
- Foody, G.M. and D.S. Boyd. Mapping tropical forest biophysical properties from coarse spatial resolution satellite sensor data: applications of neural networks and data fusion. 2003.

- Gitelson, A.A. 2004. Wide Dynamic Range Vegetation Index for Remote Quantification of Biophysical Characteristics of Vegetation. *Journal of Plant Physiology* 161:165-173.
- Hill, M.J. and G.E. Donald. 2003. Estimating spatio-temporal patterns of agricultural productivity in fragmented landscapes using AVHRR NDVI time series. *Remote Sensing of Environment* 84(3):367-384.
- Huete, A.R., H.Q. Liu, K. Batchily, and W. van Leeuwen. 1999. A Comparison of Vegetation Indices over a Global Set of TM images for EOS-MODIS. *Remote Sensing of Environment* 59:440-451.
- Huete, A., K. Didan, T. Miura, E.P. Rodriguez, X. Gao, and L.G. Ferreira. 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment* 83:195-213.
- Ichii, K., A. Kawabata, and Y. Yamaguchi. 2002. Global correlation analysis for NDVI and climatic variables and NDVI trends: 1982-1990. *International Journal of Remote Sensing* 23(18):3873-3878.
- Jakubauskas, M.E., D.R. Legates, and J.H. Kastens. 2001. Harmonic Analysis of Time-Series AVHRR NDVI Data. *Photogrammetric Engineering & Remote Sensing* 67(4):461-470.
- Jakubauskas, M.E., D.L. Peterson, J.H. Kastens, and D.R. Legates. 2002. Time Series Remote Sensing of Landscape-Vegetation Interactions in the Southern Great Plains. *Photogrammetric Engineering & Remote Sensing* 68(10).

- Lu, H., M.R. Raupach, T.R. McVicar, and D.J. Barret. 2003. Decomposition of vegetation cover into woody and herbaceous components using AVHRR time series. *Remote Sensing of Environment* 86:1-18.
- Mendoza, B., V. García-Acosta, V. Velasco, E. Jáuregui, and R. Díaz-Sandoval. 2007. Frequency and duration of historical droughts from the 16th to the 19th centuries in the Mexican Maya lands, Yucatan Peninsula. *Climatic Change* 83(1):151-168.
- Moody, A. and D.M. Johnson. 2001. Land-Surface Phenologies from AVHRR Using the Discrete Fourier Transform. *Remote Sensing of Environment* 75(3):305-323.
- Olsson, L. and L. Eklundh. 1994. Fourier Series for analysis of temporal sequences of satellite sensor imagery. *International Journal of Remote Sensing* 15(18):3735-3741.
- Reed, B.C., J.F. Brown, D. VanderZee, T.R. Loveland, J.W. Merchant, and D.O. Ohlen. 1994. Measuring phenological variability from satellite imagery. *Journal of Vegetation Science* 5:703-714.
- Schwartz, M.D., B.C. Reed, and M.A. White. 2003. Assessing Satellite-Derived start-of-season measures in the conterminous USA. *International Journal of Climatology* 22:1793-1805.
- Swets, D.L., B.C. Reed, J.D. Rowland, and S.E. Marko. A Weighted Least-Squares Approach to Temporal NDVI Smoothing. CD-ROM, 1 disc. 1999. Bethesda, Maryland, American Society for Photogrammetry and Remote Sensing.

- Viña, A., G.M. Henebry, and A.A. Gitelson. 2004. Satellite Monitoring of Vegetation Dynamics: Sensitivity Enhancement by the Wide Dynamic Range Vegetation Index. *Geophysical Research Letters* 31.
- Xiao, X., Q. Zhang, S. Saleska, L. Hutya, P. De Camargo, S. Wofsy, S. Frolking, S. Boles, M. Keller, and B. Moree III. 2005. Satellite-based, modeling of gross primary production in a seasonally moist tropical evergreen forest. *Remote Sensing of Environment* 94:105-122.

Chapter 5 Results

Results are organized in two groups: those which result from the application of the Fourier series approximation methods to land cover samples and those applied on a pixel by pixel basis to the entire study area. As stated in Chapter three, a set of analyses were carried out using sampling of the main land cover types present in the study area in order to compare the differences between them, how different they are in terms of the profile shape and how they compare. For clarification purposes, only the results from the two most contrasting vegetation types are shown (tropical deciduous forest and tropical rain forest) because it is easier to understand how the method works when comparing two contrasting vegetation types from different bioclimatic conditions. The rest of the vegetation types are assessed by the pixel by pixel analysis which was developed in order to analyze the differences between the vegetation types and the spatial context of the results. The results show the spatial pattern of the temporal behavior of all land cover types and comparisons and changes between years can be done.

As noted previously, the NDVI tends to saturate under high biomass conditions and both the EVI and the WDRVI were designed to avoid such saturation. Therefore, an evaluation of similarities and differences among the VI's is important in order to see the relationships between them and to analyze which index is most sensitive. In the second part, results of the pixel by pixel analysis are shown. These results are divided in two parts: images resulting from the Fourier parameters of the function obtained: the mean conditions (a_0 parameter) the amplitude and phase for each year and the implication of these results and the land cover/land use classification using the Fourier coefficients as input to an unsupervised classification comparing the three VI's. The simplicity and the

summarized information provided by the Fourier parameters make it easy to understand variations of the NDVI in response to climatic variability (Loyarte et al. 2008).

5.1 Comparison of Vegetation Indices

The first set of analysis was made using regions of interest (ROI's). These regions were drawn over Landsat ETM imagery and several vegetation types were analyzed (Chapter 4, section 4.5.1). However, here the results of only the two most contrasting vegetation types (Chapter 2, section 2.3.2) tropical deciduous forest and tropical rain forest are shown. Figure 26 shows a visual comparison of the multitemporal profiles throughout a five year period (starting in January 2001) of the three indices for a tropical deciduous forest vegetation type. NDVI and EVI are plotted on one axis and the WDRVI on the other. The three indexes show a strong seasonal annual pattern that represents the phenological characteristics of the tropical deciduous forest and clear dry/wet seasons. The trajectories of the three indices are similar coincide with the findings reported by Wardlow, et al. (2007) analyzing crops in Kansas, Central USA. The NDVI shows a more smoothed profile with higher values compared with the EVI. This behavior can be interpreted as less saturation and increased sensitivity as reported by Brown, et al. (2007). The EVI and the WDRVI show more variability particularly during the growing season stage. The maximum, minimum and range for this are series shown in

Table 5. It can be seen that the dynamic range is wider for the WDRVI which indicates more sensitivity. 67 out of 115 values have a NDVI value greater than 0.7 which represents almost 60% therefore saturation of the NDVI is expected more than half of the time.

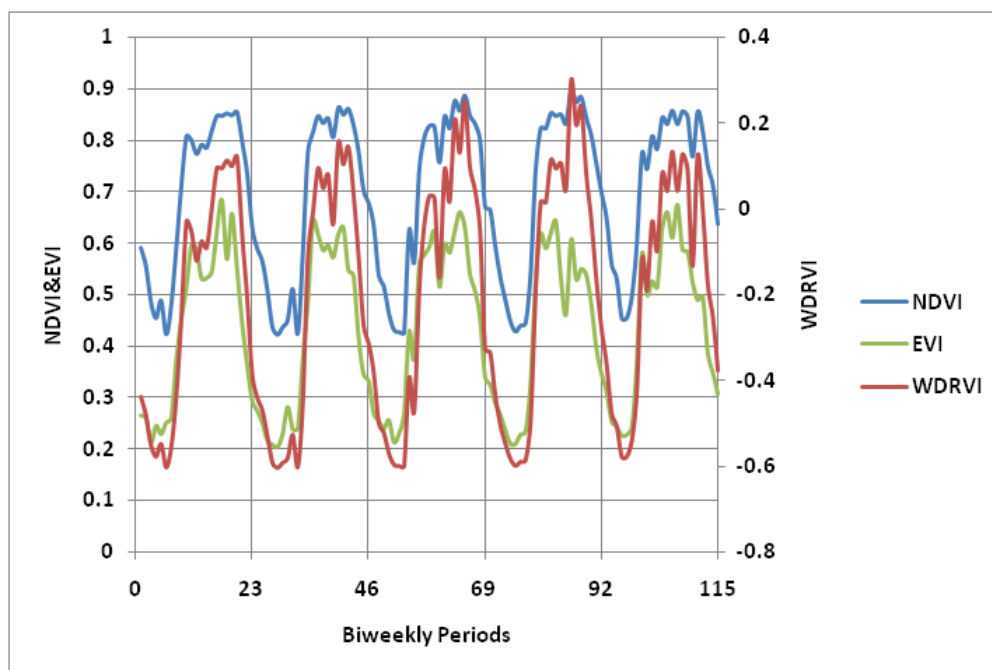


Figure 26 NDVI, EVI and WDRVI comparison over five years for tropical deciduous forest.

	Red-NIR	NDVI	EVI	WDRVI
Minimum	0.11	0.42	0.20	-0.60
Maximum	0.44	0.90	0.68	0.30
Range	0.33	0.47	0.48	0.90

Table 5. Maximum, minimum and range of vegetation indexes of tropical deciduous forest sample

Annual profiles plots of the three VIs plus the NIR-Red relationship are shown (Figure 27 to Figure 31). In all cases, the EVI shows the most variation during the peak of the growing season followed by the WDRVI which also increases the dynamic range during that period (biweekly periods 10 to 21). The NDVI has a more smoothed profile with subtle variations. The NIR-Red profile is very similar to the EVI. In 2001, the peak during the growing season starts in the biweekly period 10 for the NDVI and WDRVI cases (lower value for the WDRVI) whereas the EVI is shifted to the right (between biweekly periods 11 and 12). Also there is a local minima for the EVI in the biweekly

period 19. For the 2002 case, the three indices follow a parallel pattern except that EVI shows a local *maxima* in the biweekly period 12 and a lower value in the 19. In 2003, the three indices also follow a parallel pattern with no major differences. The year 2004 shows higher values for the EVI in the beginning of the growing season (maxima in the biweekly periods 11 and 14) and a local minimum in period 16. For 2005 we see a parallel pattern similar to 2003. Lower values in 2003 and 2004 for the EVI could be explained by the lower precipitation during the months of July in 2003 and July and August in 2004 (Table 10). According to this, it can be concluded that the EVI is more sensitive to changes than the WDRVI or the NDVI. In all the cases, the NIR-Red shows a parallel trajectory compared with the EVI. Also in all the cases, it is noticeable that the EVI drop has a lower slope at the end of the growing season.

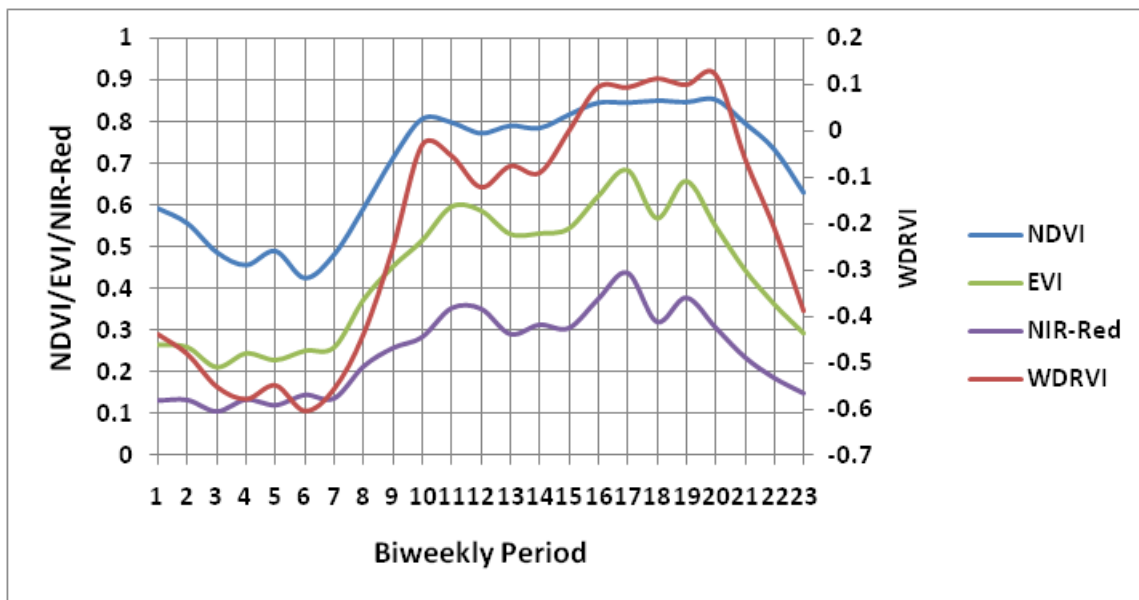


Figure 27. 2001 index comparison for a tropical deciduous forest site. The EVI and NIR-Red show more local variation in time and VI value whereas the other two indices have a similar pattern.

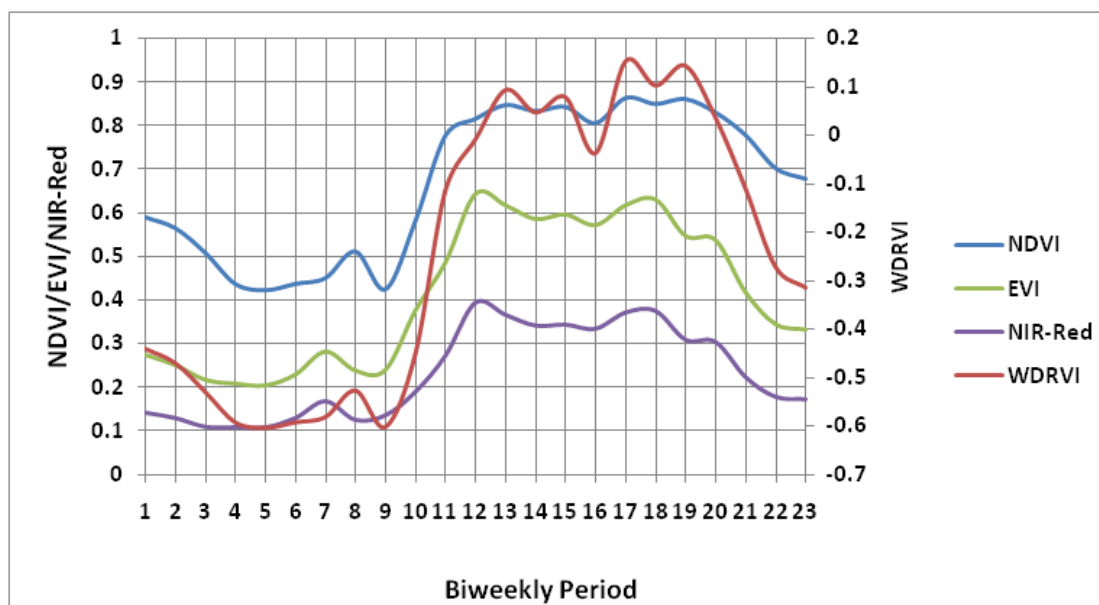


Figure 28. 2002 index comparison for a tropical deciduous forest site. The EVI and NIR-Red show more local variation in time and VI value whereas the other two indices have a similar pattern.

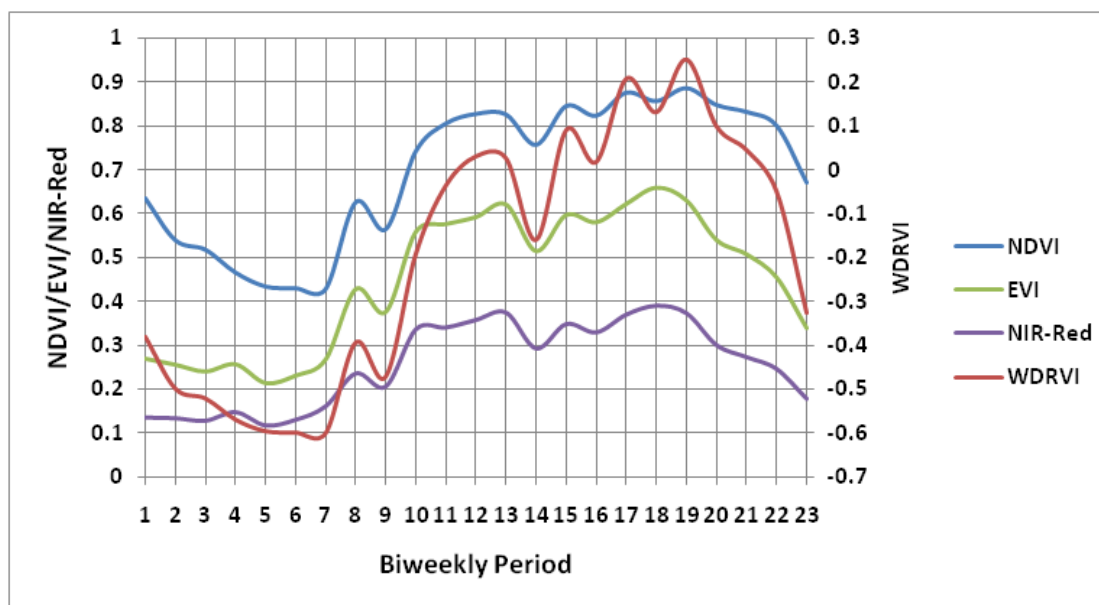


Figure 29 2003 index comparison for a tropical deciduous forest site. The EVI and NIR-Red show more local variation in time and VI value whereas the other two indices have a similar pattern.

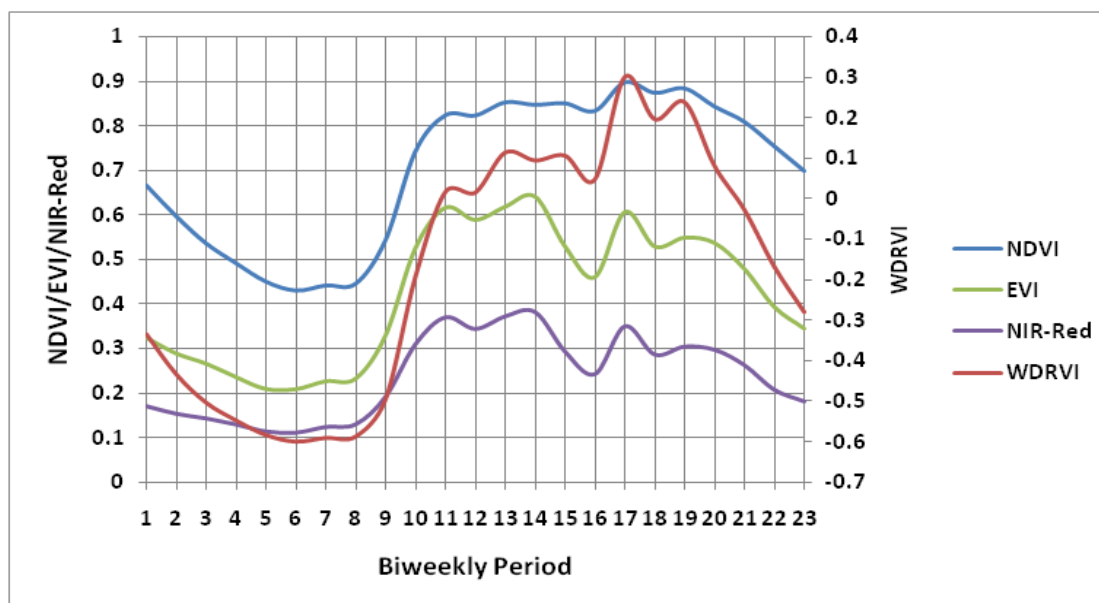


Figure 30. 2004 index comparison for a tropical deciduous forest site. The EVI and NIR-Red show more local variation in time and VI value whereas the other two indices have a similar pattern.

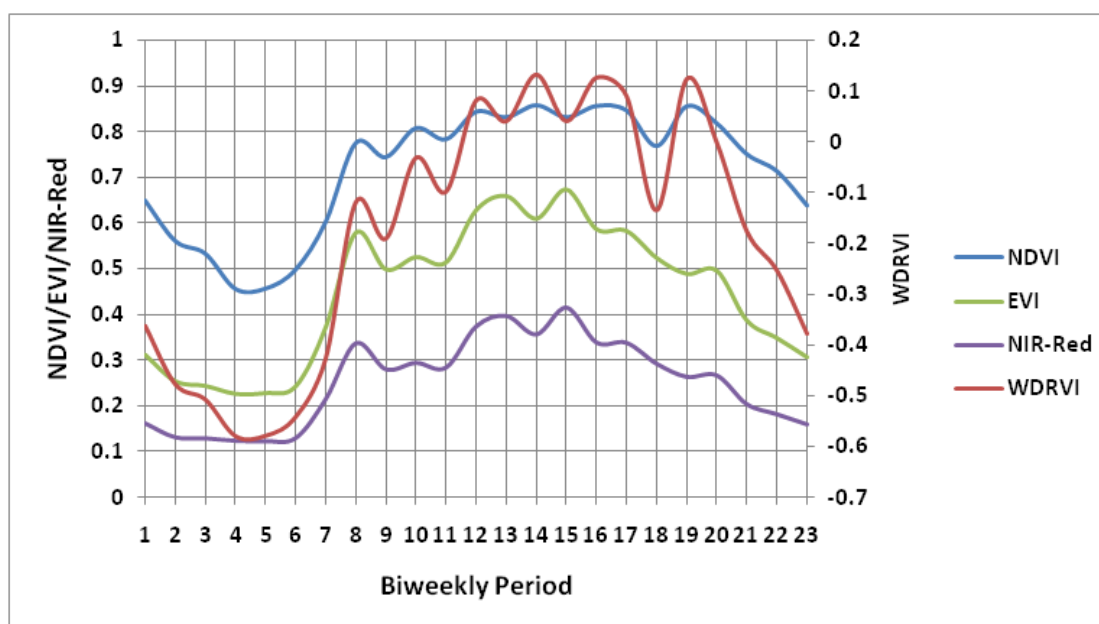


Figure 31. 2005 index comparison for a tropical deciduous forest site. The EVI and NIR-Red show more local variation in time and VI value whereas the other two indices have a similar pattern.

Statistical correlations (Pearson and Spearman) and a cross-correlation were run between each index and the precipitation grouped by biweekly periods. The cross-correlation is the statistical correlation of two variables as a function of a lag which specifies the signed distances between the elements of one of the variables. Table 6 shows the values of such correlations. In all the cases the EVI is the index with higher values compared with the other two, however the correlations are low. The standard Pearson correlations (0.56 for the EVI) the Spearman correlation values which are the result of a ranked correlation are higher (0.72 in the EVI case). Higher values of cross correlations are for the EVI and WDRVI with a lag of one and NDVI with a lag of two which means that the displacement between the precipitation and vegetation response is around fifteen days (one biweekly period). This analysis shows that the EVI is the index most highly correlated with the precipitation.

	Pearson Correlation	Spearman Correlation	Cross- correlation
NDVI	0.45	0.64	0.53
EVI	0.56	0.72	0.58
WDRVI	0.48	0.64	0.58

Table 6. Statistical correlations of vegetation indices versus precipitation (tropical deciduous forest case).

Figure 32 shows the five year profiles of a tropical rain forest site. In all the cases the VIs response is very noisy probably due to the atmospheric effects; however the EVI and the NIR-Red relationship show an annual cyclical pattern (lows and highs in five cycles) compared with the other indices where the annual pattern is not evident. In order to reduce atmospheric effects, a moving window average smoothing process was applied to

the data. Figure 33 shows the same five cycles (annual pattern) of the EVI and NIR-Red whereas in the NDVI and WDRVI no pattern is shown clearly. The higher seasonal contrast of the EVI was reported by Ratana, and Huete (2004) in several vegetation types including evergreen forests.

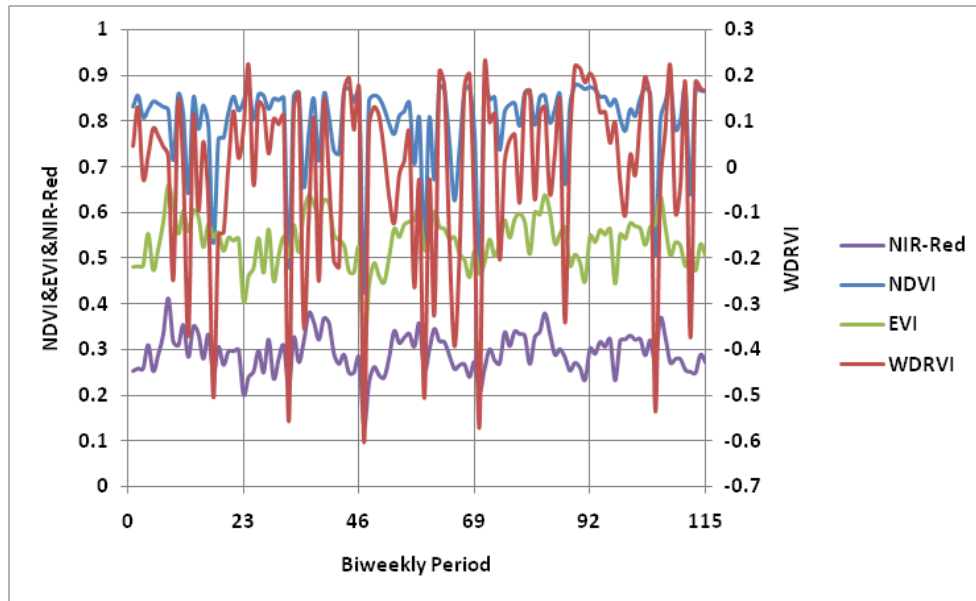


Figure 32. Five year data for tropical rain forest. The EVI shows a seasonal behavior (annual increase and decrease of the value). Index values look very noisy.

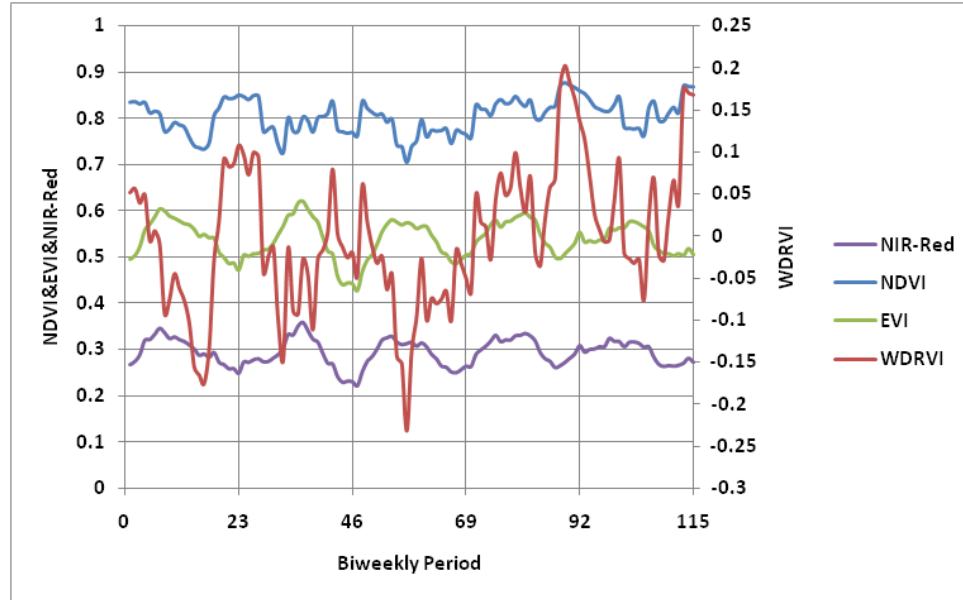


Figure 33. Five year smoothed data for tropical rain forest. The EVI shows a seasonal behavior (annual increase and decrease of the value).

Calculating the maximum minimum and range for this series shown in Table 7, it can be seen that the dynamic range is much wider for the WDRVI which indicates higher sensitivity. Considering that a NDVI value of 0.7 is very high, in this case 103 out of 115 values are higher than that value which represents almost 90%, therefore saturation of the NDVI is expected most of the time. By comparison, the EVI has a wider range than the NIR-Red relationship.

	Red-NIR	NDVI	EVI	WDRVI
Minimum	0.13	0.42	0.30	-0.60
Maximum	0.41	0.88	0.66	0.22
Range	0.28	0.46	0.36	0.83

Table 7. Maximum, minimum and range vegetation indexes of tropical rainforest sample

Figure 34 to Figure 38 show the smoothed VIs annual profiles for the tropical rain forest sample. In all the years, the EVI and NIR-Red follows a curve which increases at

the beginning of the year and decreases at the end (see for example 2002). For all the years the EVI is more stable than the other indices. The NDVI show a more flattened pattern with slightly variations throughout the year. These variations may be due to atmospheric effects and are drastically increased by the WDRVI.



Figure 34. 2001 Index comparison for a tropical rainforest site. The EVI shows a seasonal pattern similar to the precipitation regimen whereas the other two indices show the opposite.



Figure 35. 2002 Index comparison for a tropical rainforest site. The EVI shows a seasonal pattern similar to the precipitation regimen. The other two indices in this year, also approach the seasonal pattern but still have noisy data.

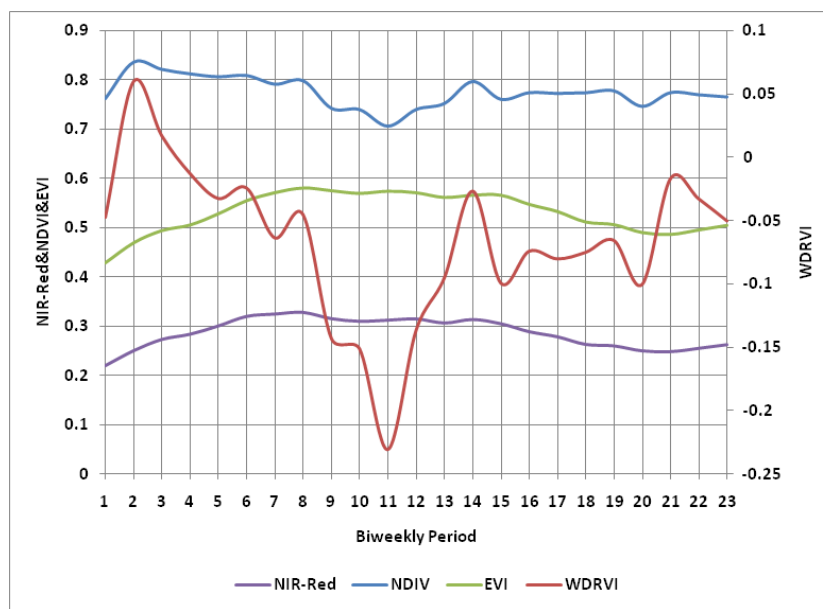


Figure 36. 2003 Index comparison for a tropical rainforest site. The EVI shows a seasonal pattern similar to the precipitation regimen. The other two indices in this year, also approach the seasonal pattern but still have noisy data.

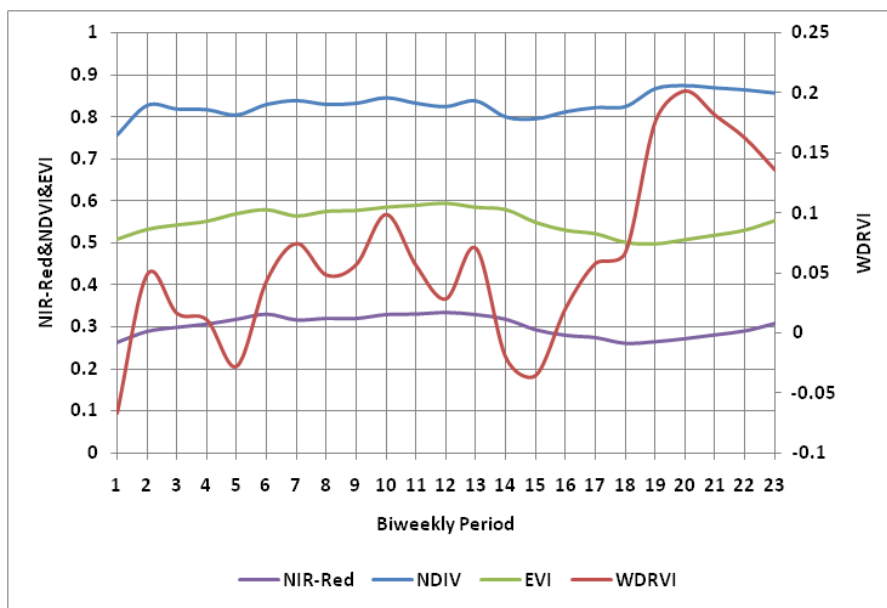


Figure 37. 2004 Index comparison for a tropical rainforest site. The EVI shows a seasonal pattern similar to the precipitation regimen. The other two indices in this year, also approach the seasonal pattern but still have noisy data.

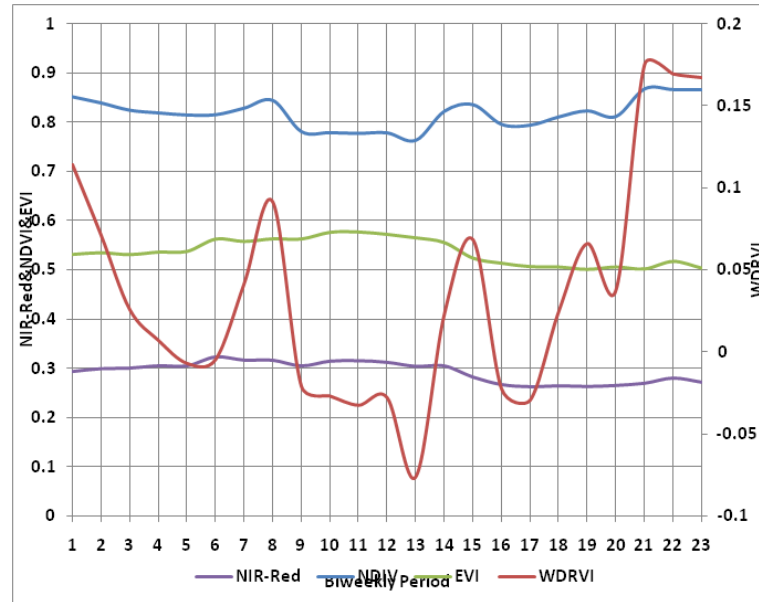


Figure 38. 2005 Index comparison for a tropical rainforest site. The EVI shows a seasonal pattern similar to the precipitation regimen. The other two indices in this year, also approach the seasonal pattern but still have noisy data.

Table 8 shows the statistical correlations for the tropical rain forest case. Values are very low for the Pearson correlation (the highest for EVI is only 0.12). Higher values are evident for the ranked correlation (Spearman) for the NDVI and WDRVI, and the highest for the cross correlation applying a lag value of one is the EVI.

	Pearson correlation	Spearman Correlation	Cross-correlation
NDVI	0.03	0.78	0.03
EVI	0.12	0.09	0.19
WDRVI	0.01	0.78	0.02

Table 8. Statistical Correlations of vegetation indices versus precipitation (tropical rainforest case).

According to this analysis the EVI is better correlated to precipitation than the NDVI or the WDRVI for the tropical deciduous forest. In the case of the tropical rainforest the correlations are very low which means that variations in the amount of precipitation throughout the year are not picked up by the VI's although the EVI is the index with higher correlations.

Cross plots were used to assess relationships of the magnitude of pairs of indices. Figure 39, show the relationship between the NDVI and EVI for the tropical deciduous forest, tropical rain forest and smoothed tropical rain forest. There is a nonlinear relationship for these indices more clearly shown in the case of the tropical deciduous forest (the trend line and R^2 value of 0.88 corresponds to this type of vegetation). The tropical rainforest points have a clustered pattern. Using the smoothed data the pattern is still clustered and there is a nonlinear trend similar to the tropical deciduous forest case. Figure 40, show the nonlinear relationship of the NDVI vs WDRVI for tropical deciduous forest and tropical rainforest samples. The trend line and R^2 value of 0.99 (polynomial of second order) are for both cases. The tropical deciduous forest points are continuous whereas the tropical rainforest points are more dispersed and grouped in the higher values. Figure 41 shows the EVI versus WDRVI also for tropical deciduous forest and tropical rainforest. Despite the dispersion of the points, there is a linear relationship between both indices for the tropical deciduous forest case ($R^2=0.88$), the tropical rainforest samples, are clustered in the higher values with no clear pattern.

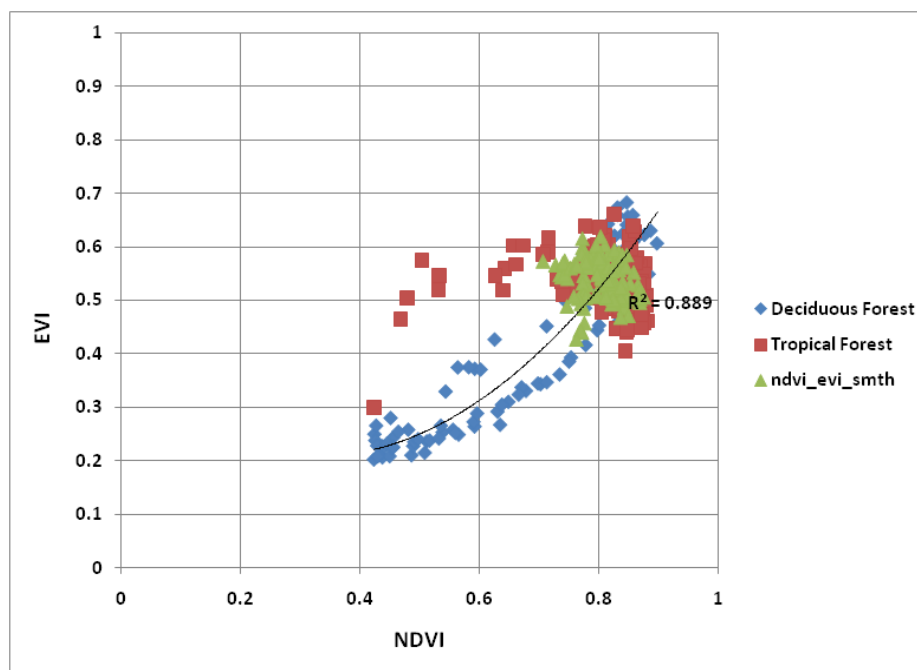


Figure 39. NDVI versus EVI relationship. The trend line and R^2 value is for the tropical deciduous forest.

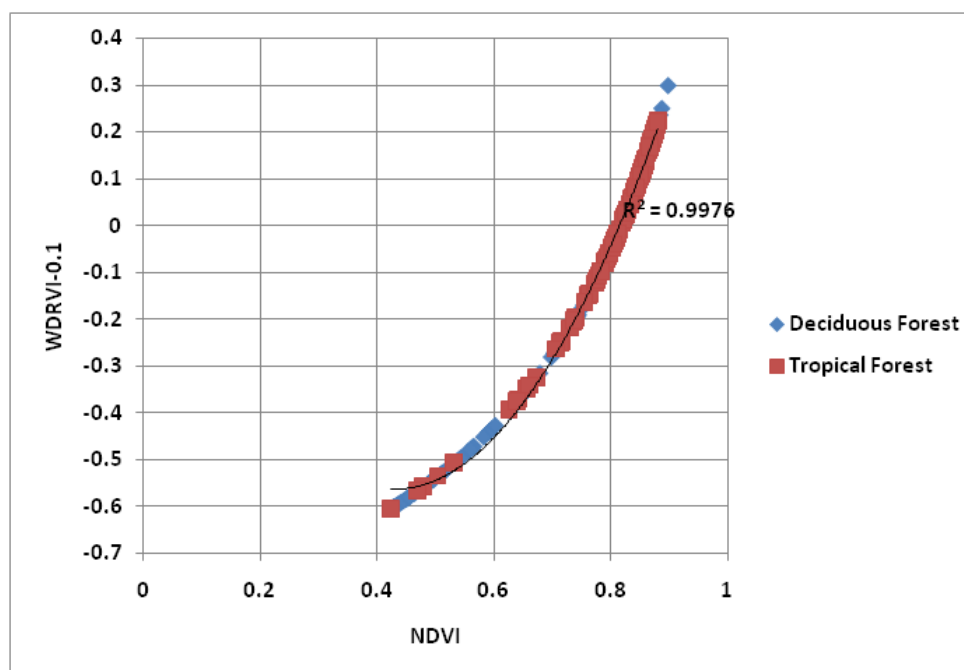


Figure 40. NDVI versus WDRVI relationship (notice the non-linear relationship between them)

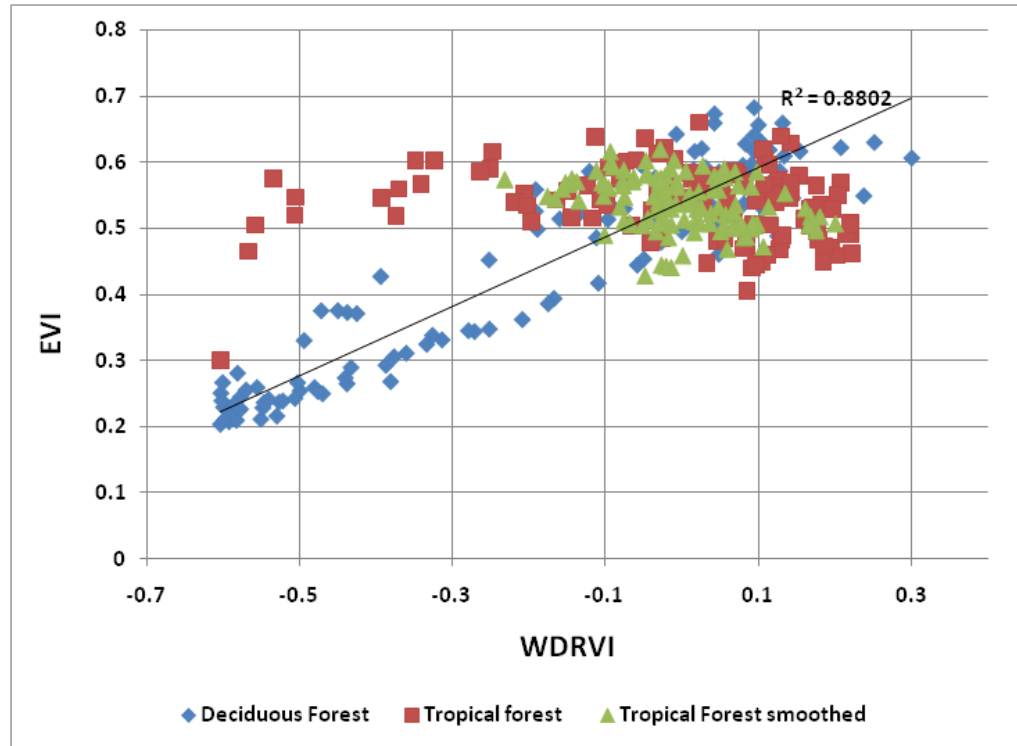


Figure 41. EVI versus WDRVI relationship

As mentioned before, the three indices rely on the NIR and Red relationship. The following graphs show the behavior of the VIs against the NIR-Red for the tropical deciduous forest (Figure 42) and tropical rainforest (Figure 43). The NDVI and WDRVI show an asymptotic behavior as both values increase, less pronounced for the WDRVI and highly linear relationship for the EVI with very high R^2 value of 0.98. In the case of the tropical rainforest the linear relationship of the EVI and the NIR-Red is maintained with a lower slope value and a lower R^2 (0.88) compared with the previous case. The cluster of points of the NDVI and WDRVI show no clear trend with the NDVI. The WDRVI shows more dispersion with a higher range of values.

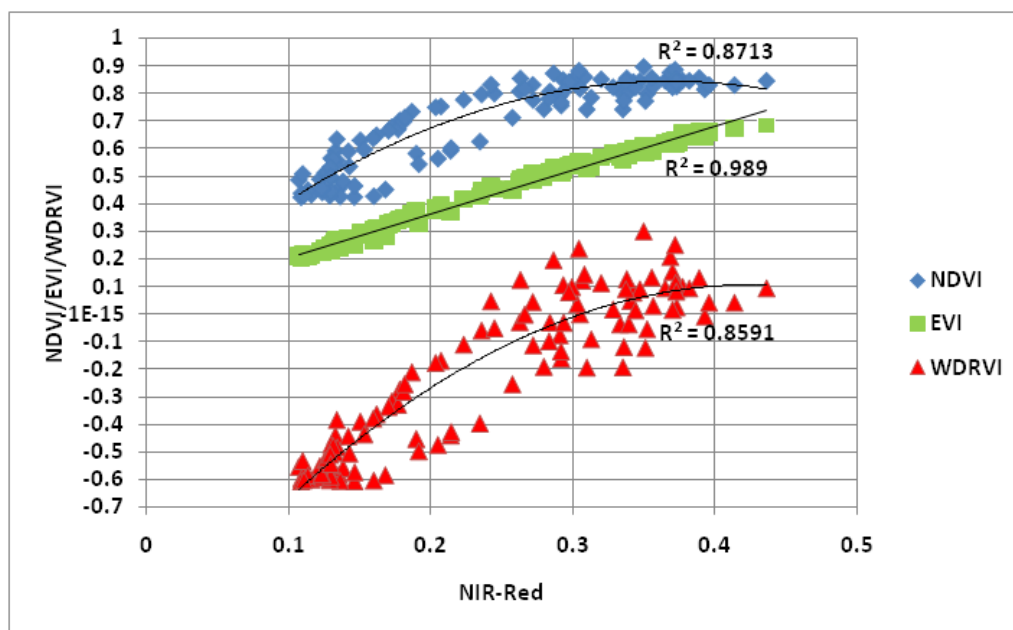


Figure 42. NIR-Red vs vegetation indices. Tropical deciduous forest case.

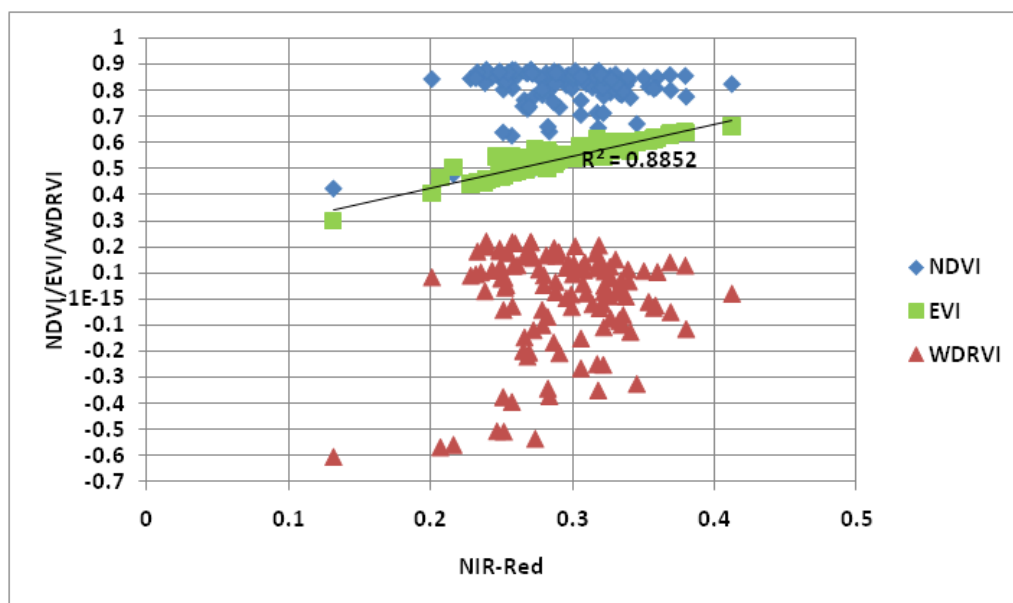


Figure 43. NIR-Red vs vegetation indices. Tropical rainforest case.

Comparison of the indices is even more complex additional information about biophysical properties of vegetation is not available. The EVI responds to scattering reflectance and is more sensitive to slight changes of vegetation response during the

maximum of the growing season but the WDRVI avoids the saturation of the NDVI under high biomass conditions increasing the range and therefore the sensitivity. In fact the results suggest that the WDRVI (and the NDVI as well) are indicators of greenness whereas the EVI could be more related to the structure of vegetation and therefore the indices are complementary tools that can both be useful depending of the objective. The EVI was found to be better correlated to precipitation than the NDVI or the WDRVI for the tropical deciduous forest. In the case of tropical rain forest the correlations are very low which means that variation in the amount of precipitation throughout the year is not picked up by the VI's although the EVI is the index with higher correlated.

The tropical deciduous forest vegetation index profile shows a behavior strongly affected by seasonal components (dry/wet seasons) by contrast, the tropical rain forest shows slight variations through time. Wavelet analysis decomposes the time series into a space of time-frequency. The Morlet wavelet method was used to determine dominant modes of variability and how these modes vary in time (Torrence and Compo 1998). By means of this type of analysis periodicities (annual, semi-annual, etc) of time series are evaluated. In this case it was used to characterize each of five year vegetation index profiles (2001-2005) and compare the differences between them. The following graphs show the results of this analysis for the three VI's analyzed and different vegetation types. The first set of graphs is for tropical deciduous forest (Figure 44 NDVI, Figure 45 EVI and Figure 46 WDRVI).

In the upper part of the graphs the five year profile raw data is shown. The central part of the graph shows the global wavelet power spectral density; red tones represent higher densities whereas blue tones low densities. The U-shaped curve show the

influence of boundary effect and the contours indicate the 95% confidence level. The global wavelet spectrum is shown in the left part of the graph where period of one means annual period, 0.5 six month period 0.25 three month period. The dashed line indicates the 95% confidence level.

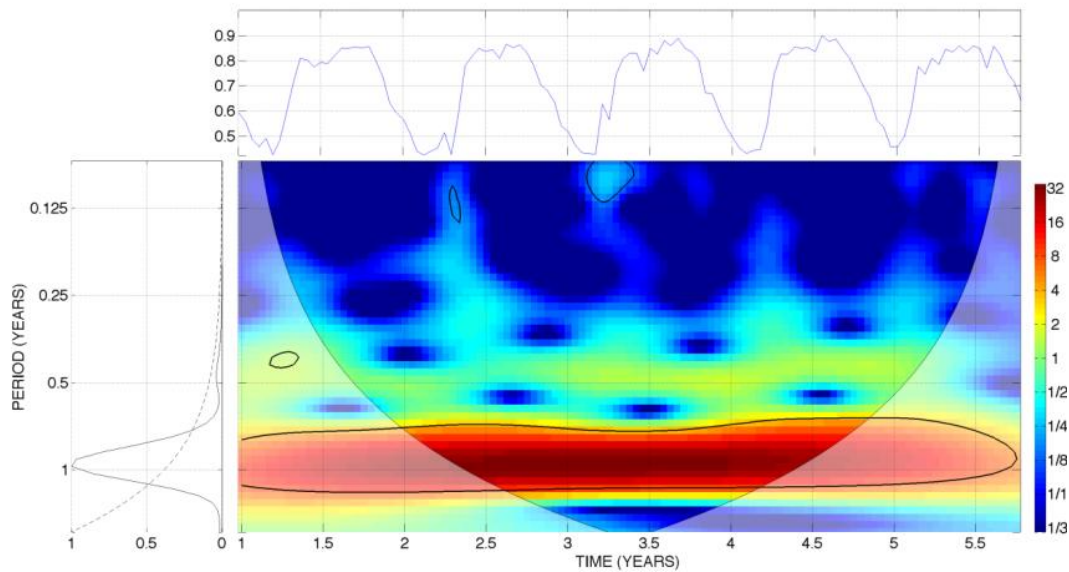


Figure 44. Tropical deciduous forest NDVI wavelet spectrum. The graph shows a strong annual period (value of 1)

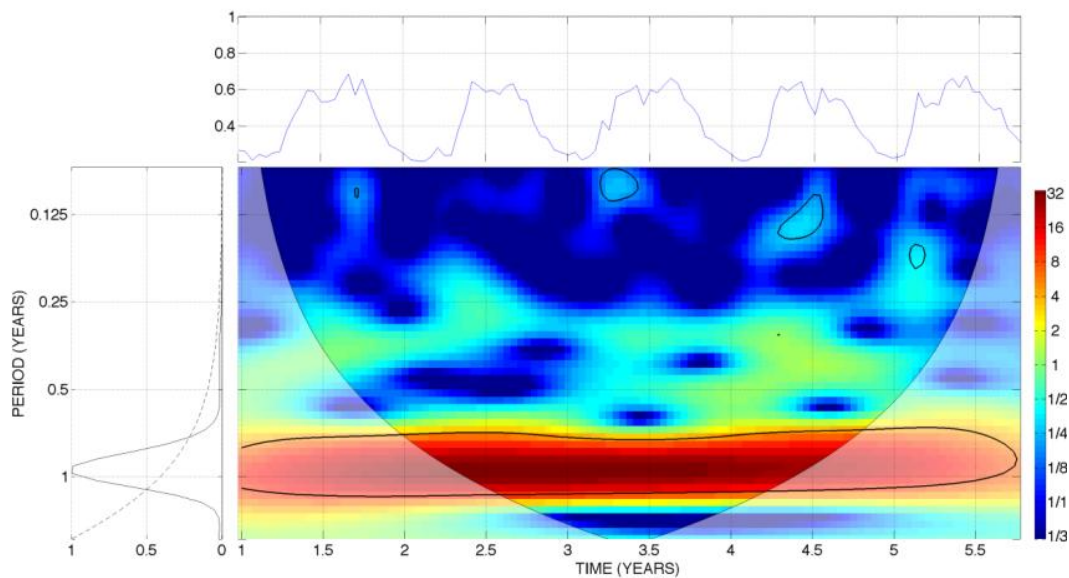


Figure 45. Five year, tropical deciduous forest EVI wavelet spectrum. The graph shows a strong annual period (value of 1). Also local variations of less periods of time are detected (closed isolines less than a period of 0.25)

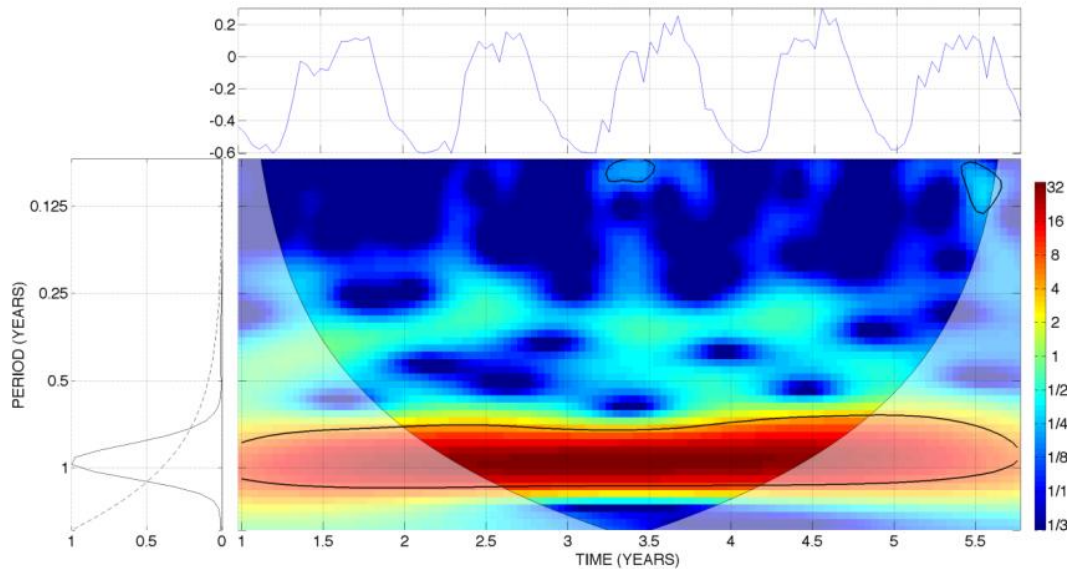


Figure 46. Five year, tropical deciduous forest WDRVI wavelet spectrum. The graph shows a strong annual period (value of 1) similar to the NDVI case.

The three indices show a strong and continuous annual periodicity with no major differences between them this agrees with the precipitation regime with strong dry and wet seasons. Only the NDVI shows a very slight, almost imperceptible, six month period not present in the other indices. The EVI global spectrum also shows very lower periodicities less than one month. These periodicities (shown in cyan tones surrounded by black contours) are present in all the years except 2002 and can be explained by local minima values since the precipitation regime in all the area has a midsummer drought effect which means that usually there is lower precipitation between two *maxima* during the raining season (Chapter 2, section 2.1.1) These local minima values are not located at the same time. In 2001, the *minimum* is located late in the growing season, 2002 and 2005 are located earlier and 2004 in the middle. Compared with the precipitation values, there is higher precipitation in the month of May than in June, 2003 and 2005 shows higher early precipitation during the month of June; in particular June 2005 was

extremely high, even higher than September which is normally the rainiest month. The NDVI and WDRVI only agree with the EVI in the 2003 variation. (monthly precipitation values are shown in Table 10).

The second set of graphs show the wavelet analysis for the tropical rain forest sample. As described early in this Chapter, the VI's of this type of vegetation show no clear seasonal pattern. The discontinuities of the index values through the year could be explained by the presence of clouds that were not removed during the composite process. The wavelet spectrum of the NDVI (Figure 47) shows a low discontinuous annual periodicity most intense during 2001 and 2002, and even a higher three month period which cannot be explained as a vegetation response to precipitation (Chapter 3, Section 3.5).

The EVI wavelet spectrum (Figure 48) shows an annual period, stronger in the mid years (2002-2004) but not as strong and continuous as the tropical deciduous forest case (Figure 45). Besides this pattern, no other clear periodic pattern can be detected. The low periodicities (less than a month) did not match with any precipitation variation.

The WDRVI wavelet spectrum graph (Figure 49) shows a higher annual period stronger in the first two years and discontinuous for the rest of the analyzed period, compared with the NDVI and also shows a three month and lower period which again cannot be explained with precipitation.

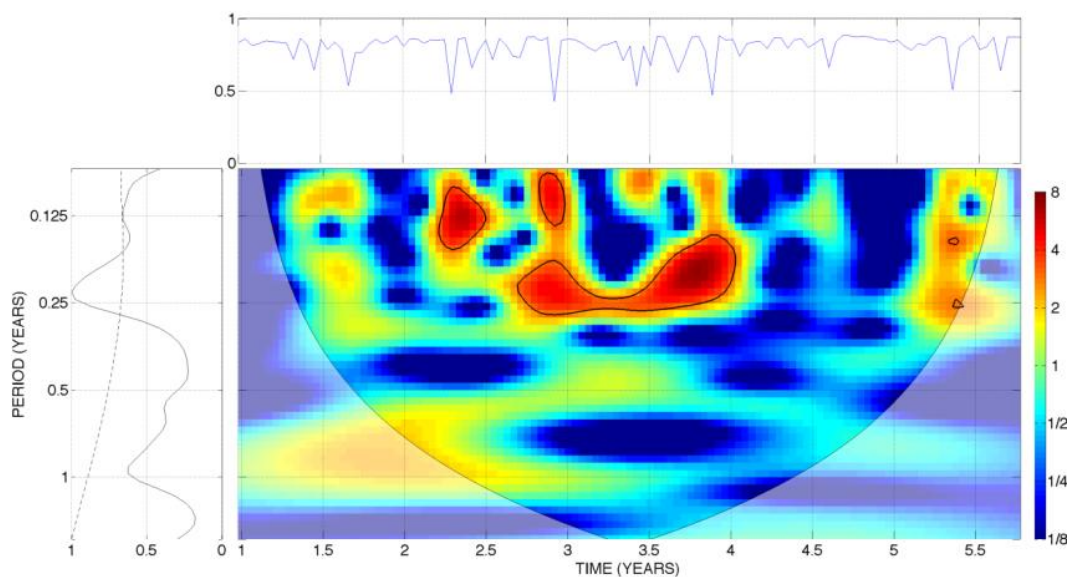


Figure 47. Five year, tropical rainforest non-smoothed NDVI wavelet spectrum. The maximum period is in 0.25 of a year, followed by the annual (Period = 1).

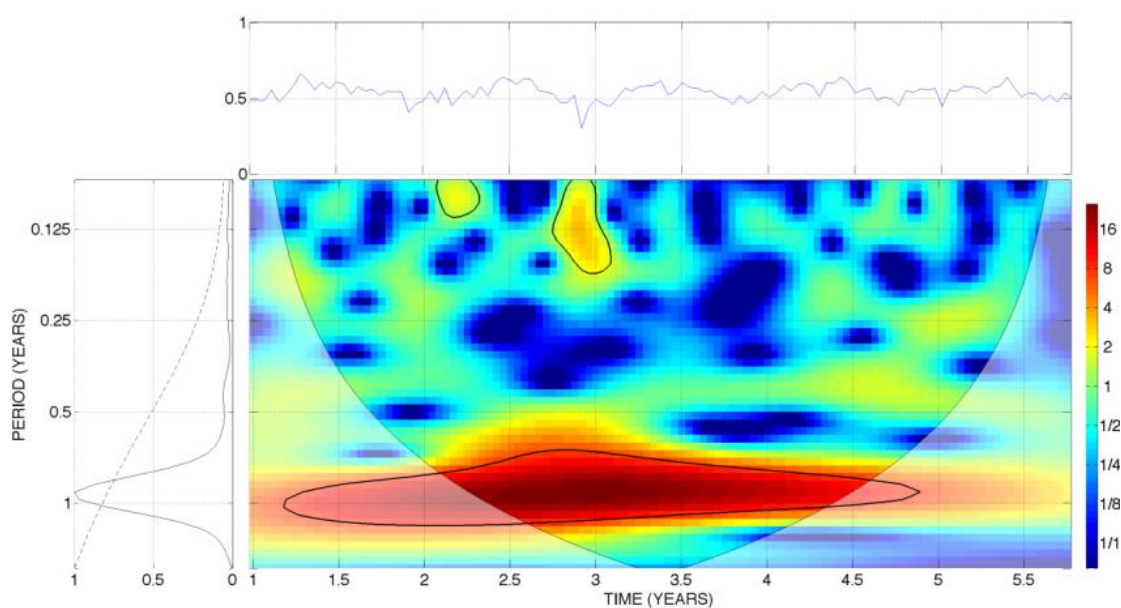


Figure 48. Five year, tropical rainforest non-smoothed EVI wavelet spectrum. In contrast with the other VI's in this case, annual period is clearly marked.

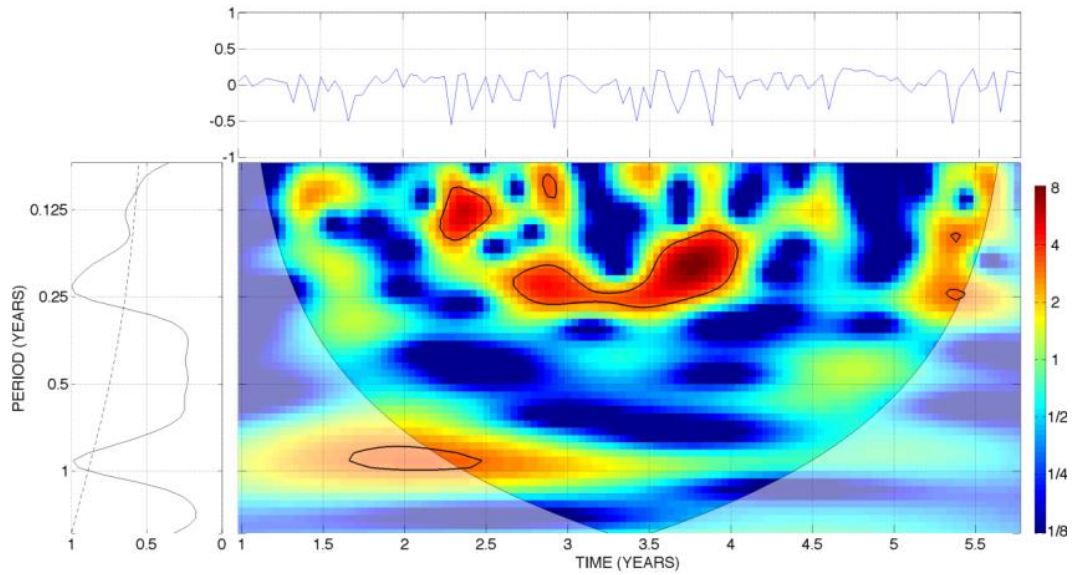


Figure 49. Five year, tropical rainforest non-smoothed WDRVI wavelet spectrum. The period of 1 (annual) is more clearly shown than the NDVI but less than the EVI and it is stronger during the first two years. It is still an important period of 0.25 of year probably related to noise and spurious data.

In order to clean the spurious variations present in the signal, a moving window average smoothing procedure was applied to the three tropical rainforest samples then the wavelet analysis was applied again. The following graphs show the results after the smoothing process.

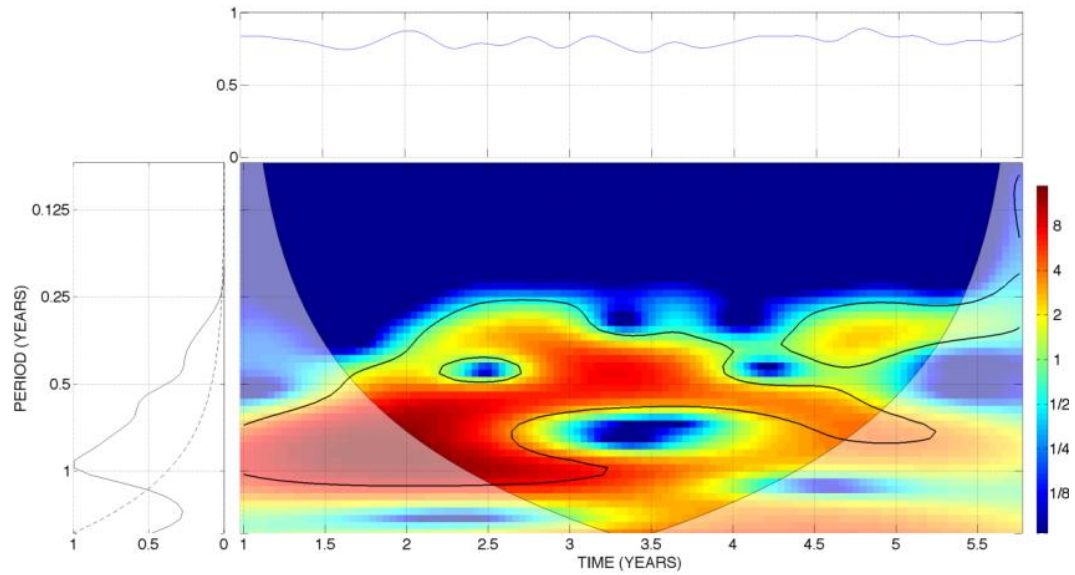


Figure 50. Tropical rainforest NDVI (smoothed) wavelet spectrum. Compared with the non-smoothed data, the period of 1 (annual) is more clearly marked. It is still strongest in the beginning of the series.

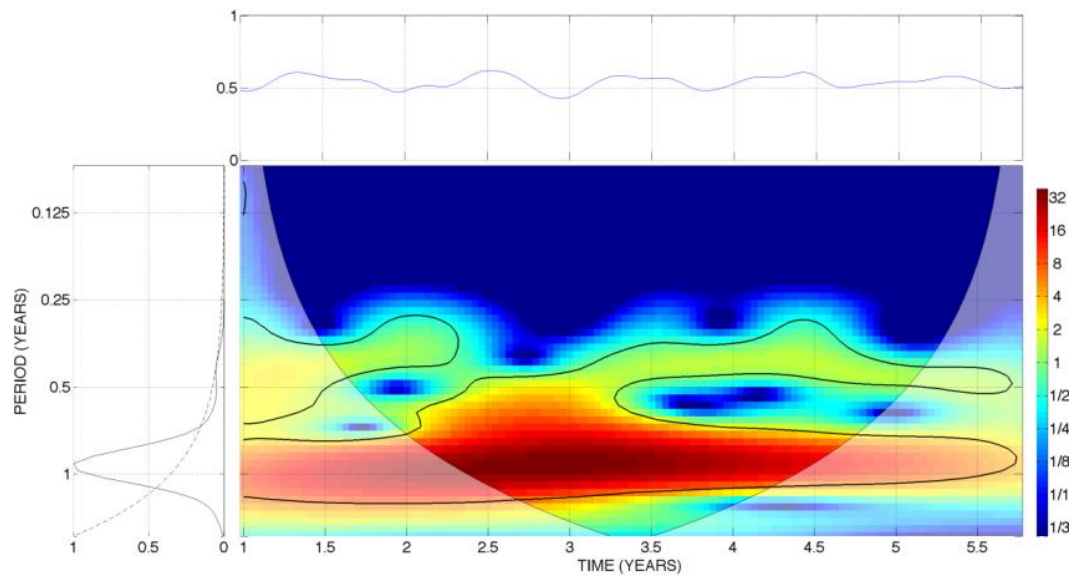


Figure 51. Tropical rainforest EVI (smoothed) wavelet spectrum. After the smoothing process, the annual period is more clearly marked. The periods less than one are eliminated.

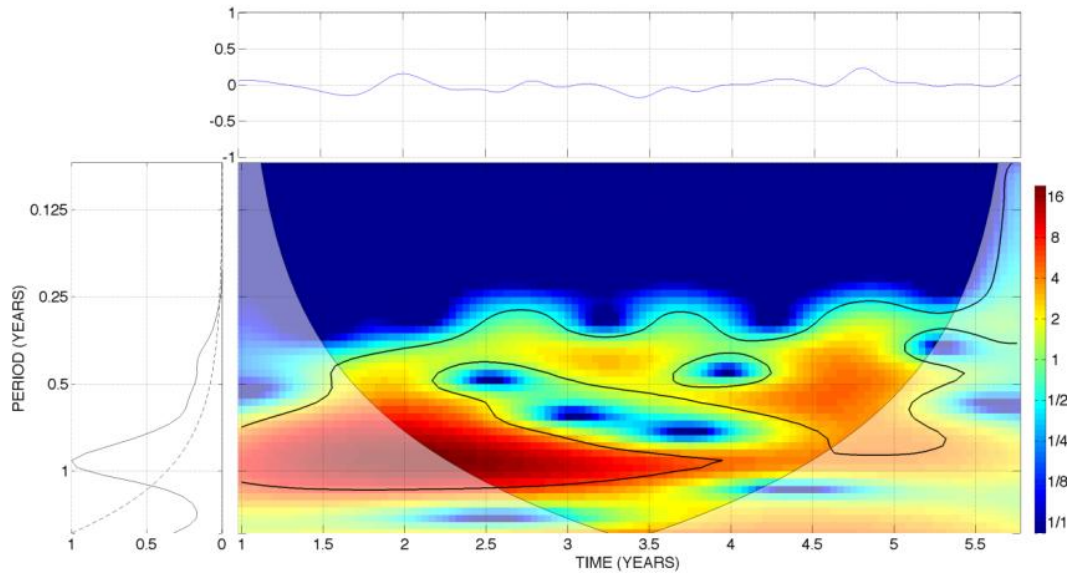


Figure 52. Tropical rainforest WDRVI (smoothed) wavelet spectrum. The period of 1 is clearly marked at the beginning of the time series. Stronger compared with the non-smoothed data.

The smoothing process resulted in the annual period becoming the main component in the NDVI and the WDRVI (Figure 50 and Figure 52) although it is still not continuous through time and some lower periods (six month and less) still occur. By contrast, the EVI (Figure 51) shows a stronger and continuous annual period and the low periods practically disappear. The precipitation regime for this type of vegetation (described in Chapter 2, section 1.1) shows a very high total precipitation (usually greater than 3500 mm per year) but not regularly distributed throughout the year. There is more precipitation during the summer (June to September). The precipitation shows more than the EVI response. The stronger annual period shown in Figure 51 at the middle of 2002 and the beginning of 2003 (2.5 to 3 years) can be explained because the month of June 2002 was the highest for the whole year and the beginning of 2003 was very dry in particular the month of April (Table 12). The flat profile in 2005 can be explained because in 2005 the month of June was extremely wet with 545 mm of precipitation.

Other vegetation types such as annual crops, sugar cane plantations, and tropical grass show similar results (not shown) than the tropical deciduous forest case. Temperate forest which is also an evergreen vegetation, also shows many variations probably due to the presence of clouds which are not completely removed by the composite procedure. A particular case is the irrigated crops sample (Figure 53) which shows a strong and continuous annual periodicity and also a more or less continuous six-month period which can be explained by two agricultural cycles. The six-month period was strong in 2001 and 2005 and continuous (yellow to orange tones) throughout the year.

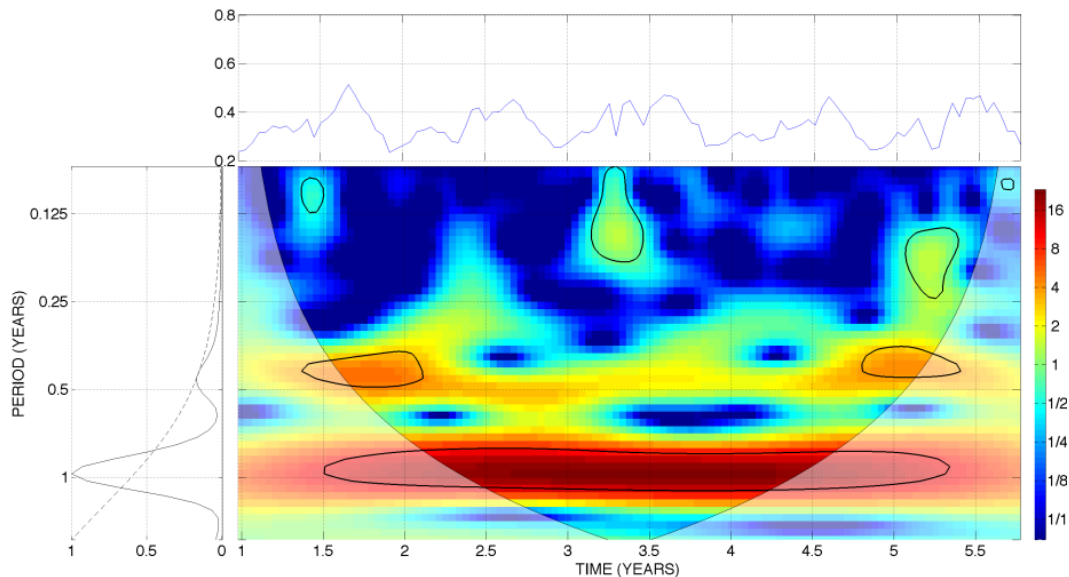


Figure 53. Irrigated crops EVI wavelet spectrum. The annual period is stronger, but also a period of 0.5 of year (six months) is shown.

Results from the wavelet analysis suggest that the EVI is the index that shows the strongest seasonal component and also shows lower periodicities which can be related to phenomena such as the mid-summer drought.

Another technique to analyze the performance of an index by means of a sensitivity index was calculated using Equation 5 as proposed by Viña et al. (2004).

Values of $Sr < 1$ indicate conditions where the NDVI is more sensitive than the WDRVI and vice versa. Figure 54 shows the relative sensitivity of three samples of tropical rain forest and one sample of tropical deciduous forest (23 values per sample). Tropical rain forest has high biomass conditions throughout the year. Since the tropical deciduous forest is a vegetation type with strong seasonality (a dry season-low biomass contrasting with wet season characterized by well vegetated high biomass conditions), it is used as baseline. It is expected that the WDRVI will be more sensitive than the NDVI for the tropical rain forest cases because there are fewer points below the relative sensitivity limit than over the limit. In the case of the tropical deciduous forest there are many points under the limit which indicates that the NDVI is still sensitive. However, compared with the results from Viña et al. (2004) the percentage of persistence of enhanced WDRVI sensitivity (percentage of the points over the relative sensitivity limit) is very high. The highest percentage reported by Viña et al. (2004) is 59% for the Southern Central Plains ecoregion followed by 53% in the Blue Ridge Mountains ecoregion. In this study the tropical deciduous forest has 65% persistence and the three tropical rainforest samples are over 87% with the highest at 91%. The NDVI cross-over value for the tropical deciduous forest is 0.4 which is relatively low. This suggests that for tropical areas, even in cases of vegetation with strong seasonality, the WDRVI is more sensitive most of the time. As suggested by Viña et al. (2004) the optimal value for α has to be better defined particularly in tropical areas because it is a function of the density of vegetation and thus requires further research. However for low LAI values, or early in the green-up, or late during senescence, the NDVI will perform well. Finding a threshold where the breaking point occurs could lead to use a combination of the two indices for better performance.

The same procedure was tried between the NDVI and EVI and between the EVI and WDRVI, but the results were inconsistent and therefore are not presented here.

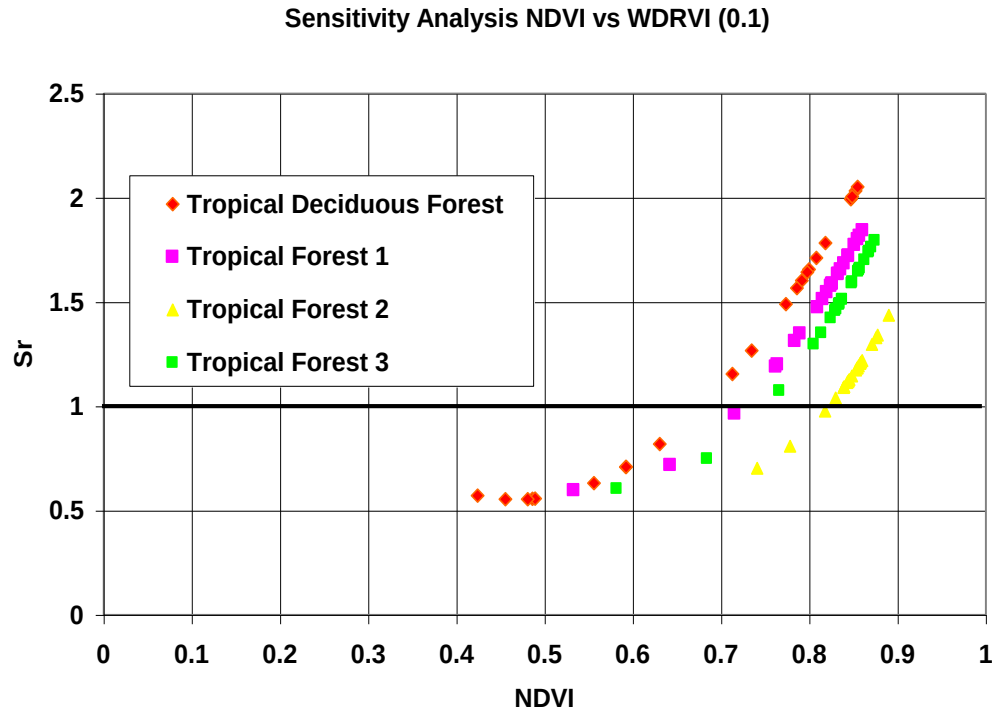


Figure 54. Relative sensitivity of NDVI and WDRVI. Values below 1 means that the NDVI performs better.

5.2 Fourier Series Analysis Results

As stated in Chapter 4, The Fourier series approximation method was chosen to characterize the temporal profiles. By obtaining the optimal parameters for each profile, land cover types can be characterized and also changes between years can be determined. The EVI images were chosen to do this procedure because it seems that this index is the one that best identifies the seasonal differences and local differences during the growing season.

5.2.1 Amplitude and Phase Angle Parameters

Optimal amplitudes and phase angle values of each temporal profile were obtained applying Equation 7. As stated, it is expected that the amplitude (c_k) and phase angle (ϕ_k) values vary for each land cover/land use types according to their temporal behavior. Vegetation types with strong seasonality will have high amplitude values in the first harmonic contrasting with vegetation types with limited seasonality which will have low amplitude values. The amplitude value is the value of the peak of the first harmonic (first sinusoidal curve) and depends of the overall behavior of the temporal profile. High amplitude values indicate unimodal temporal vegetation index patterns where land use/cover has a wide range of values (Jakubauskas et al. 2002). The phase angle is the location value of the peak of the amplitude value and it is related to time of occurrence of the maxima (Jakubauskas et al. 2002). The constant Fourier parameter (a_0) which corresponds to the year mean value can be used as an indicator of the overall productivity for each year (Loyarte et al. 2008). Subsequent amplitudes and phase angles represent the contribution of other local effects including noise and they have less and less contribution.

Below are the results for the same group of samples shown above of two contrasting natural vegetation types (tropical deciduous forest and tropical rain forest) these show in a detailed manner the harmonic decomposition procedure and how the method works for each vegetation type for the analyzed period. Each graph shows the data profile, the estimated function values and the first three harmonics. The first group of graphs (Figure 55 to Figure 59) corresponds to tropical deciduous forest type for the analyzed period (2001-2005).

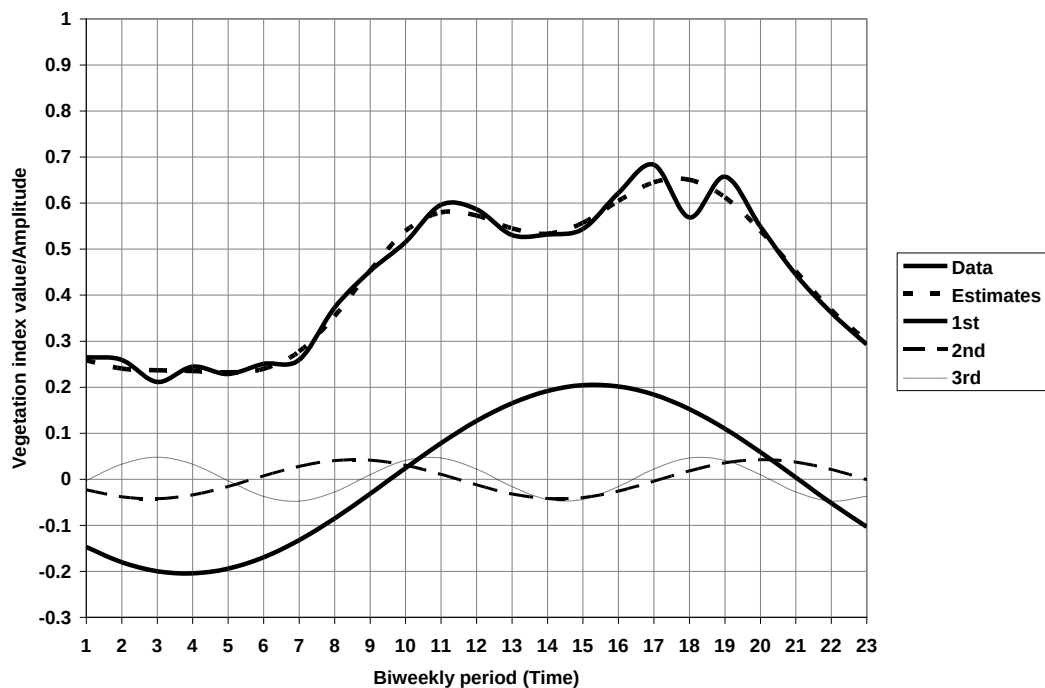


Figure 55. Tropical deciduous forest profiles 2001. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component.

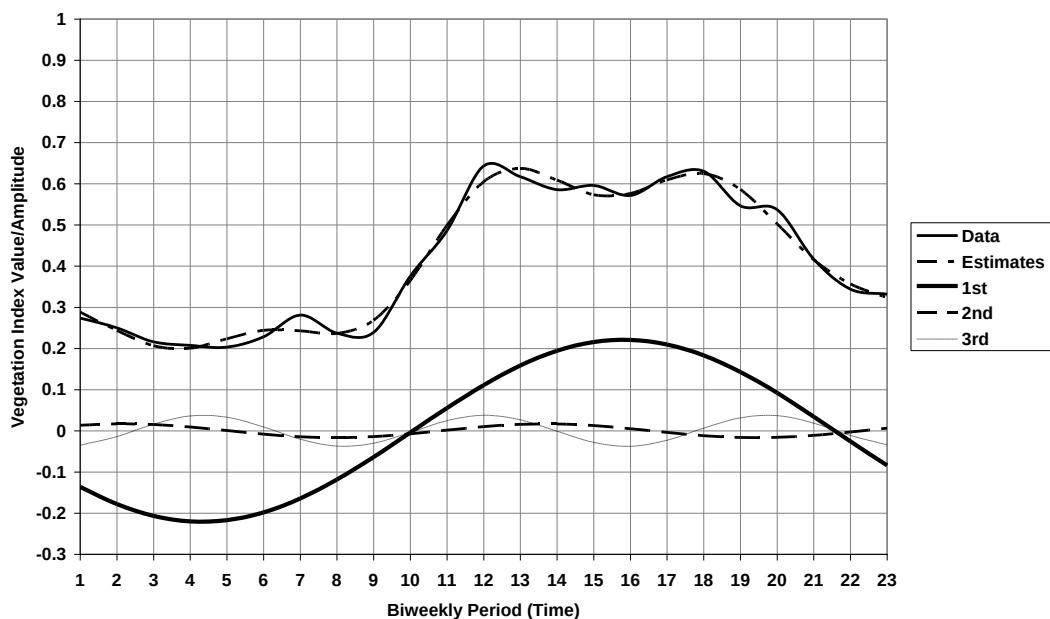


Figure 56. Tropical deciduous forest profiles 2002. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component.

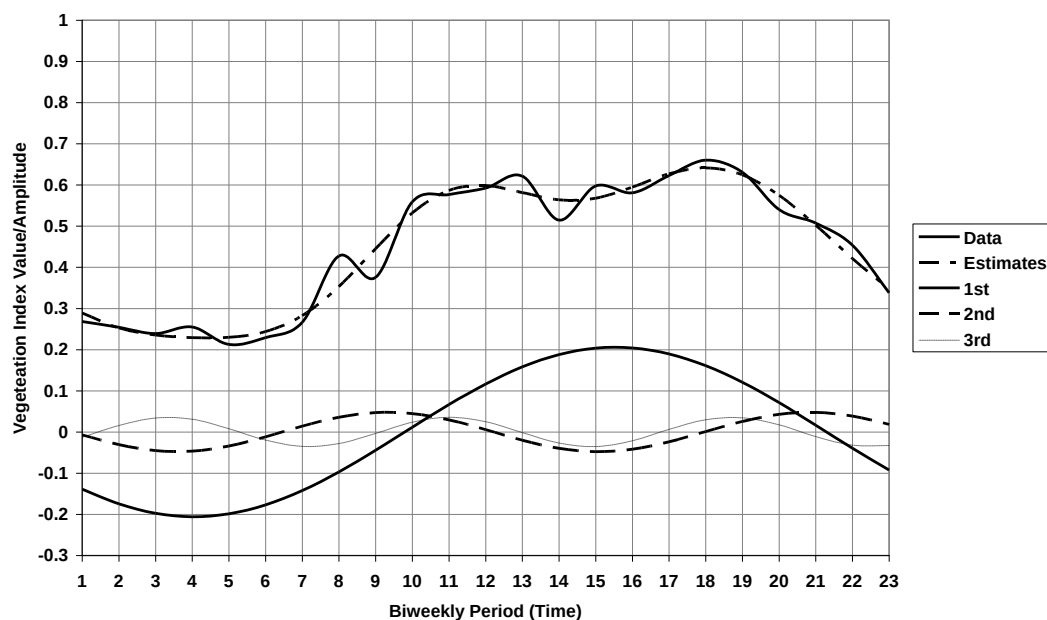


Figure 57. Tropical deciduous forest profiles 2003. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component.

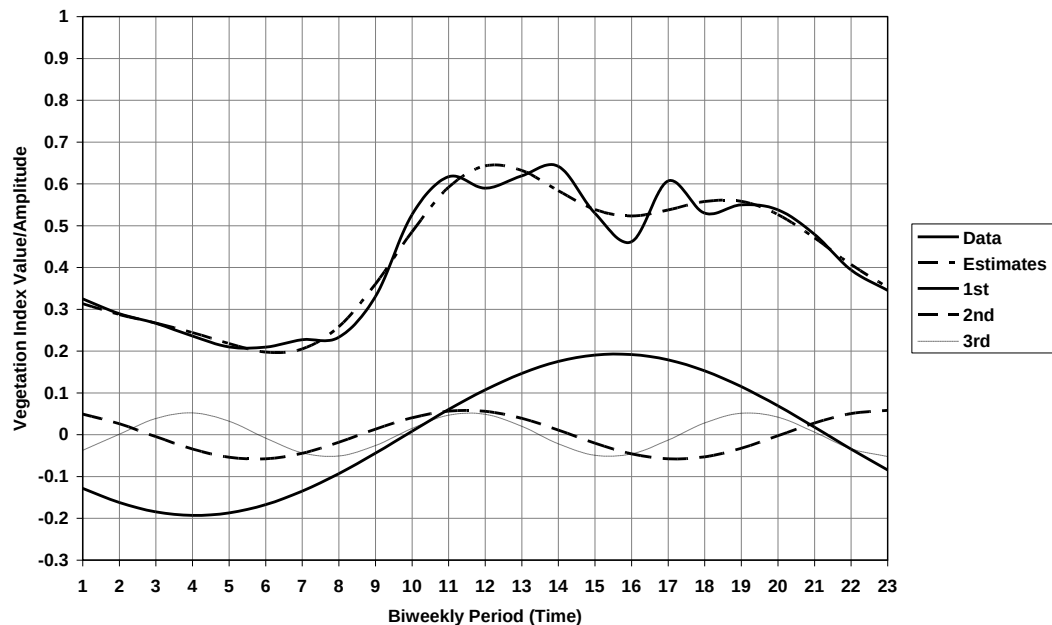


Figure 58. Tropical deciduous forest profiles 2004. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component.

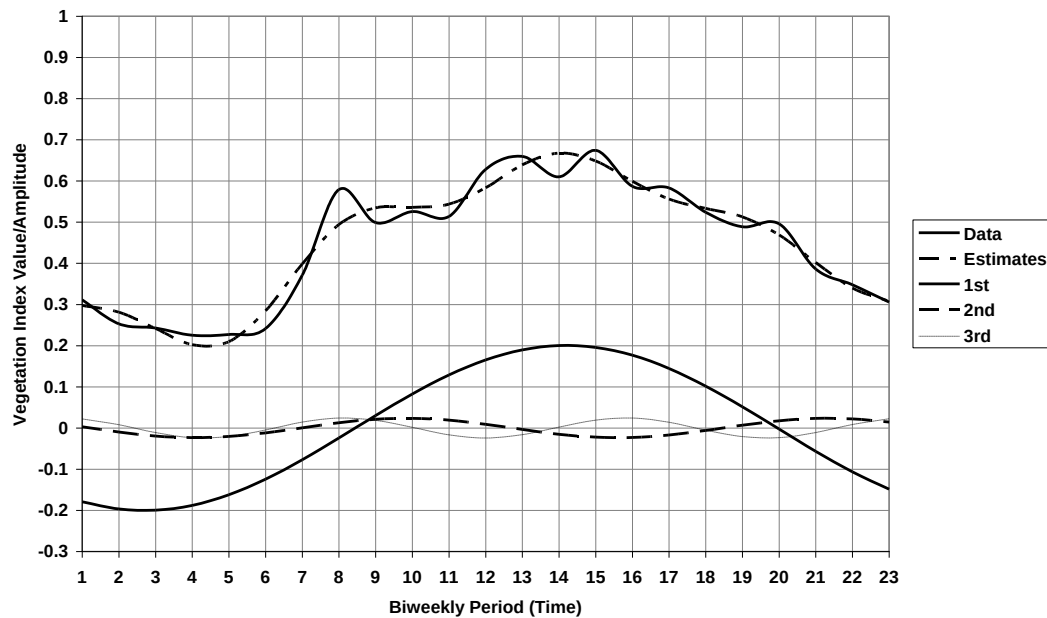


Figure 59 Tropical deciduous forest profiles 2005. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component.

The profiles are characteristic of vegetation types with strong seasonality behavior: low values increasing with a strong slope as the rainy season starts, slight variations during the rainy season showing sometimes more than one maximum value and a descent to senescence. In most of the cases the start of the season (drastic increase of the vegetation index value) is around the biweekly period 7 for 2001 and 2003 years, around 8-9 for 2002 and 2004 and around 5-6 for 2005. The slope is steepest for the years 2001, 2002, and 2004 and less steep for the years 2003 and 2005. Also the expected mid-summer drought effect is present with different intensities in all the years except in 2005 which show also a slight descent at the end of the season compared with the other years. The first harmonic curve has in all cases values with maxima around 0.2 and is located around the biweekly period 15-16.

A summary of the Fourier coefficients is shown in Table 9. The mean values (A_0) vary slightly (four tenths) as well as the first harmonic amplitude value (C_1), however they are not directly related. Maximum a_0 values do not correspond to maximum c_1 values and vice versa. In this case, it is noticeable that in most of the years the first harmonic phase (f_1) values are around the 15th biweekly period except by 2005 which has a value of 14.20 which means that the maximum amplitude value was shifted to the left for this year compared with the rest of them. Looking at the 2005 graph, it is noticeable that the vegetation index profile is wider compared with the other years with high values around the months of May-June. From the precipitation values for those years shown in Table 10, it can be seen that 2005 was a particularly rainy year with a precipitation total of more than 1400mm whereas the rest of the years are below 800mm. In particular, in 2005 the precipitation in June was extremely high compared with the previous years. This could be the explanation for the left shift in the first harmonic in this particular year.

	2001	2002	2003	2004	2005
a0	0.44	0.41	0.45	0.42	0.45
c1	0.20	0.22	0.21	0.19	0.20
c2	0.04	0.02	0.05	0.06	0.02
c3	0.05	0.04	0.04	0.05	0.02
c4	0.01	0.04	0.01	0.01	0.03
f1	15.32	15.82	15.54	15.59	14.20
f2	8.58	7.94	3.59	5.72	4.09
f3	3.00	4.38	3.37	3.89	4.32
f4	-0.85	0.78	-0.60	0.34	-0.57

Table 9. Fourier coefficients, Tropical deciduous forest. In bold are shown the mean value (a_0), the amplitude of the first harmonic (c_1), and the phase of the first harmonic (f_1).

	J	F	M	A	M	J	J	A	S	O	N	D	Total
2001		0	2	5	57	43	96	278	194	137	2	6	822
2002	1	16	5	0	24	167	99	45	265	81	22	4	731
2003	0	0	10	0	27	201	55	173	206	154	28	12	869
2004	0	2	0	5	54	90	47	66	198	169	8	0	641
2005	0	0	5	29	44	420	284	256	171	204	0	0	1414

Table 10. Monthly precipitation (mm). Aquespala weather station. Total precipitation was higher during the years 2005 and 2005 and particularly rainy in the month of June in both cases.

Figure 60 to Figure 64 show the data, estimates and the first three harmonics of a tropical rainforest sample. By contrast with the tropical deciduous forest described above (which has a strong seasonality), in this case, the temporal profile is almost flat, which corresponds to an evergreen vegetation having abundant precipitation (Chapter 2, Section 1.1). An average of 1800 mm of precipitation is distributed uniformly throughout the year. This in contrast to around 800 mm annually and a strong dry/wet seasons characteristic of the tropical deciduous forest. Nevertheless, in all the years there is a slight convexity in the profile. Some years such as 2003 and 2005 (in the raw profile and the adjusted estimates values) show local minima and maxima variations instead of a continuous profile that could be explained by remaining cloudy pixels which were not filtered completely by the compositing procedure. As a consequence of the behavior of a vegetation type with high levels of biomass and with green leaves all year, the first harmonic is also very flat with very low values. Summary of the Fourier coefficients are shown in Table 11. Mean values (Fourier coefficient a_0) are higher than the tropical deciduous case and very similar for all the years. Amplitudes (Fourier coefficient c_1) are very low in particular in the cases of the years 2004 and 2005 meaning that the profile is flatter.

In the case of the phase values of the first harmonic (Fourier coefficient f_1) is around the biweekly period 14 except for the year 2004 which is higher (14.75) and 2005 which is lower (11.25). The shift to the right in 2004 could be explained by to the lower precipitation during the month of June and the 2005 shift to the left by the high precipitation during this month similar to the tropical deciduous forest case. Precipitation values of a weather station of a tropical rain forest site are shown in Table 12.

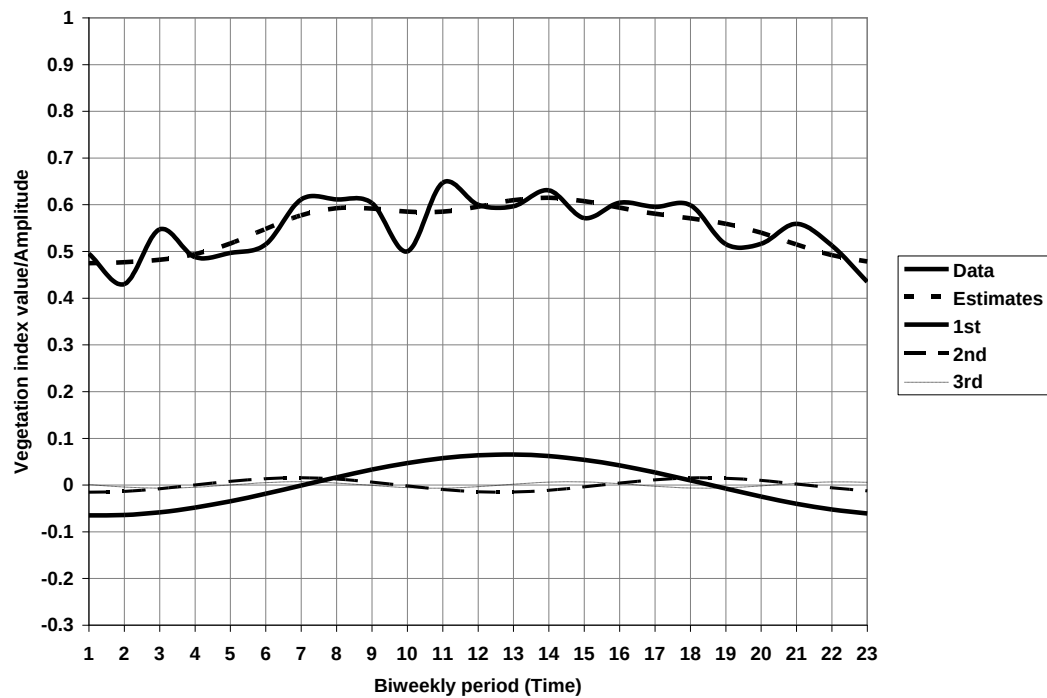


Figure 60. Tropical rain forest profiles 2001. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component.

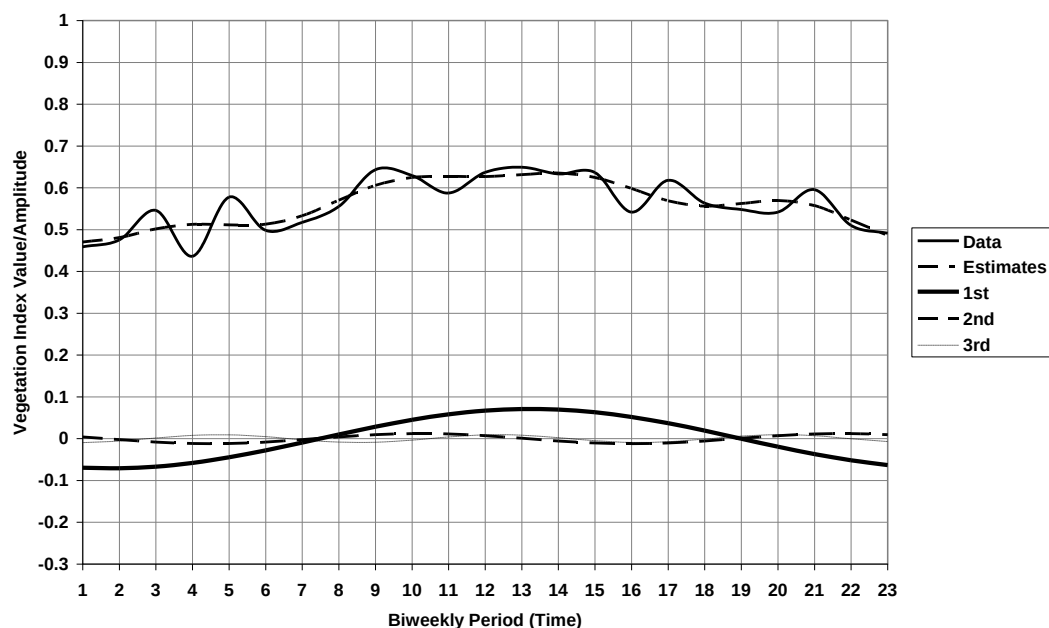


Figure 61. Tropical rain forest profiles 2002. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component.

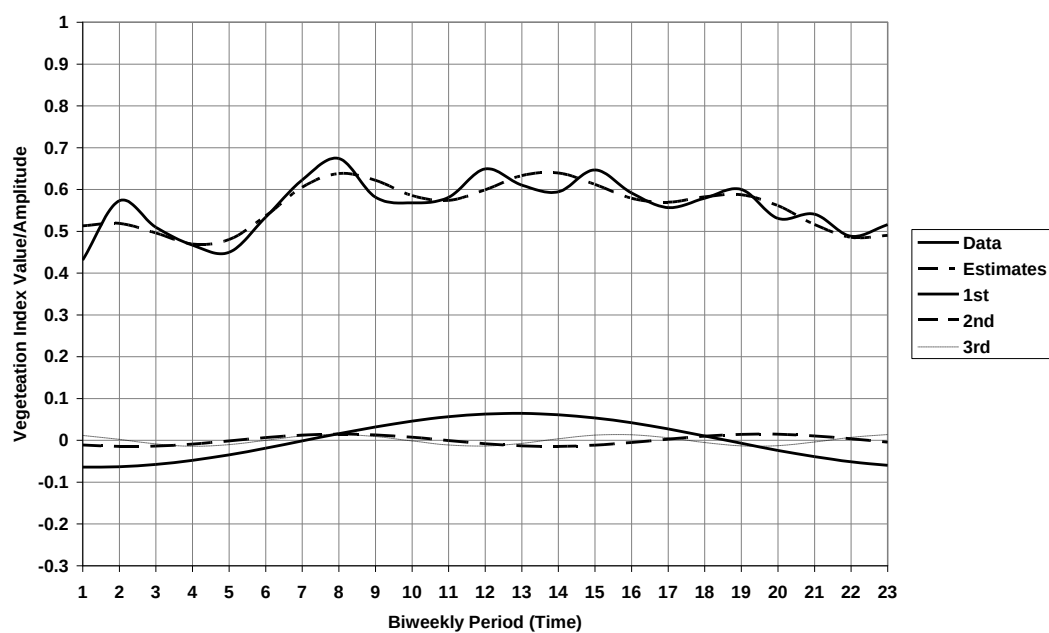


Figure 62. Tropical rain forest profiles 2003. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component.

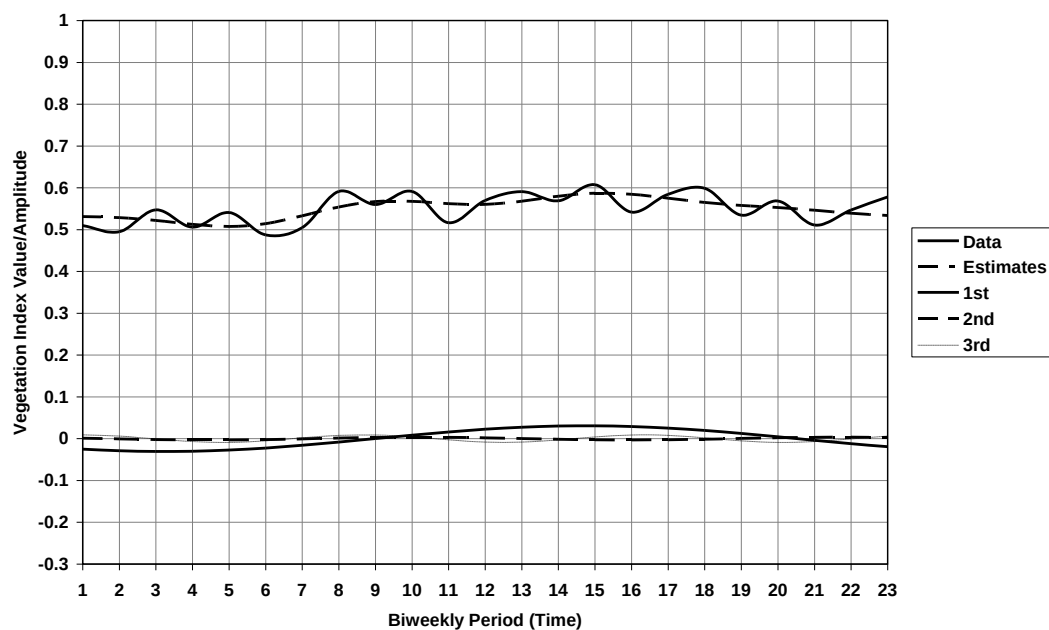


Figure 63. Tropical rain forest profiles 2004. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component.

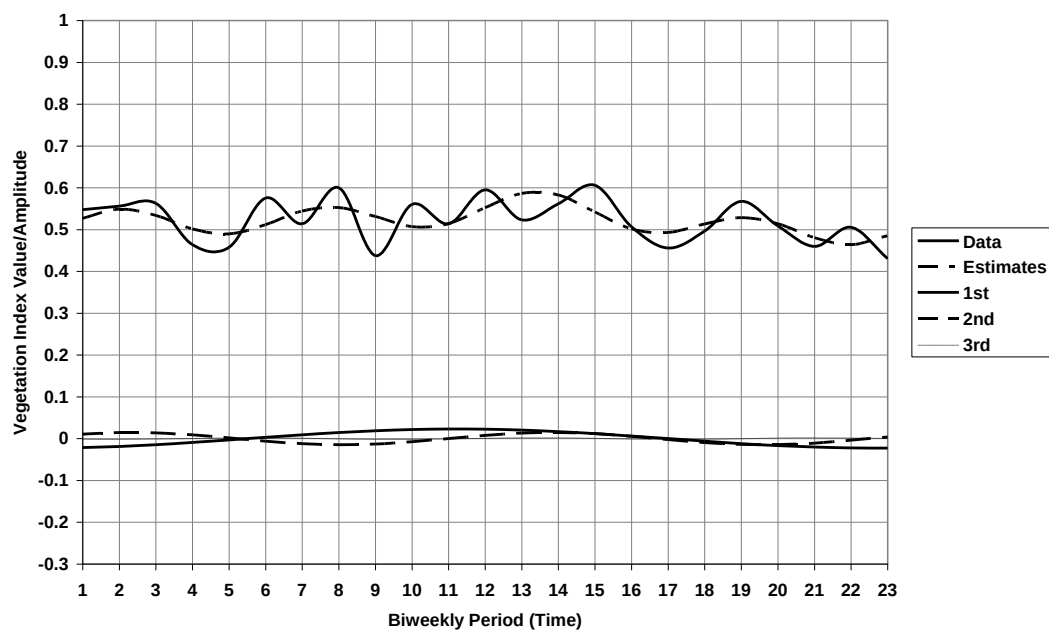


Figure 64. Tropical rain forest profiles 2005. The estimated values from the model approach the original data, the first harmonic shows the annual component, the second harmonic, the six months component and the third harmonic the four months component.

	2001	2002	2003	2004	2005
c0	0.55	0.56	0.56	0.55	0.52
c1	0.07	0.07	0.06	0.03	0.02
c2	0.02	0.01	0.01	0.00	0.01
c3	0.01	0.01	0.01	0.01	0.00
c4	0.01	0.02	0.03	0.01	0.03
f1	12.81	13.25	12.84	14.75	11.25
f2	6.88	4.50	8.06	4.42	8.10
f3	3.09	4.72	4.11	4.84	1.93
f4	-0.80	0.58	-0.88	0.22	-0.92

Table 11. Fourier coefficients Tropical rain forest. In bold are shown the mean value (a_0), the amplitude of the first harmonic (c_1), and the phase of the first harmonic (f_1).

	J	F	M	A	M	J	J	A	S	O	N	D	Total
2002	122	278	97	43	48	370	98	160	347	124	239	218	2147
2003	39	79	33	8	216	184	247	258	60	184	397	123	1832
2004	49	82	36	112	277	91	83	94	288	134	90	15	1356
2005	14	0	21	40	104	545	202	280	370	177	73	109	1940

Table 12. Monthly precipitation (mm). Boca del Cerro weather station. 2002 and 2005 were the rainiest years. 2005 was extremely rainy in the month of June.

Results of Fourier series analysis applied to two vegetation types over a five year period show the utility of the method for differentiation of vegetation types based on their temporal characteristics. The values for different years (i.e. mean value a_0 , amplitude of first harmonic c_1 , or the phase of the first harmonic f_1) are related to variations in the overall productivity, the increase or decrease of the response of vegetation to precipitation and the shift according to the time of maximum precipitation.

5.2.2 Per-pixel Analysis

Pixel by pixel calculation was done by using programs written in ENVI-IDL (Research Systems Inc, 2004). One program was used to calculate the function parameters images using Equation 6 for land cover/land use classification and the other to calculate the amplitude and phase angle images using equation 7 for change detection purposes. Selecting four harmonics or cycles, for each pixel, the programs find the optimal Fourier parameters for each pixel (a vector composed by the 23 16-day observations). Using a function fit routine called in IDL “*curvefit*” iterates until the best goodness of fit values for the function are reached. In the case of Equation 6 for each pixel the Fourier coefficients (constant, cosine and sine parameters), the standard deviations of those coefficients, the estimated values of the adjusted function and the standard error were calculated and written to the disk as separate images. In the case of Equation 7 the constant a_0 , four amplitude and four phase angle images are created as well as the estimated values, estimated error and standard deviations of the coefficients.

5.2.2.1 Mean Conditions (a_0 Fourier parameter)

The constant Fourier parameter a_0 which correspond to the annual mean value can be used as an indicator of the overall biomass productivity for that particular year (Jakubauskas et al. 2002; Xinfang et al. 2004). High values of the vegetation index indicate high total greenness over the course of a year and low values indicate low biomass or a major seasonal component. This set of images can be used as an indicator of overall change when comparing different years. The following figures (Figure 65 to Figure 67) show this parameter for the three cases (NDVI, EVI and WDRVI) in 2001. Vegetation index values were recoded in four classes: high values in dark green, medium-high in light green, medium-low in yellow and low in orange.

Figure 65. 2001NDVI Fourier a0 parameter. The Fourier a0 parameter is the arithmetic mean for the analyzed year and it is related to the overall greenness of a land cover type. High values are related to evergreen forests with less seasonal variations whereas low values are areas with more seasonal variation.

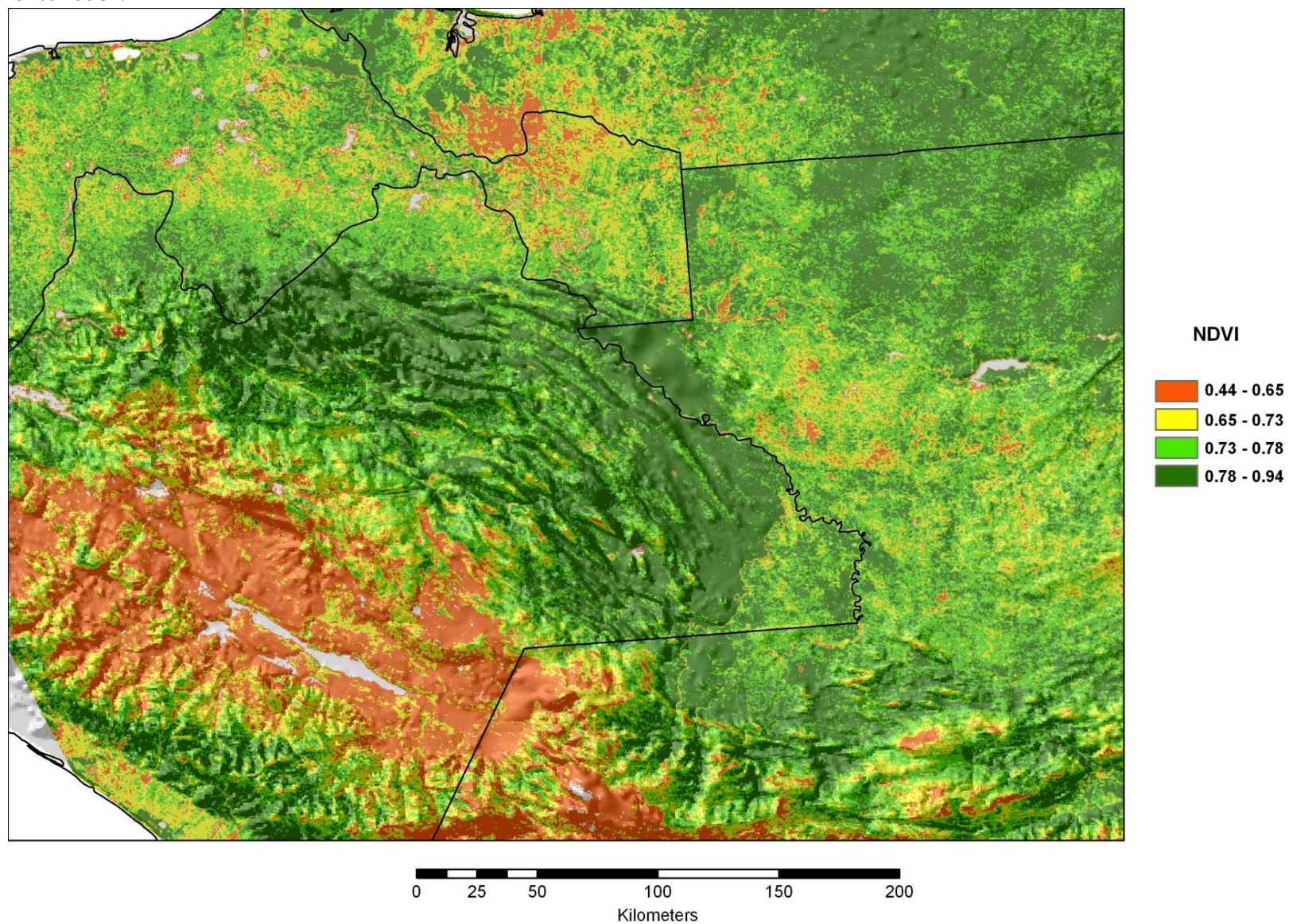


Figure 66. 2001 EVI a0 Fourier parameter. The Fourier a0 parameter is the arithmetic mean for the analyzed year and it is related to the overall greenness of a land cover type. High values are related to evergreen forests with less seasonal variations whereas low values are areas with more seasonal variation.

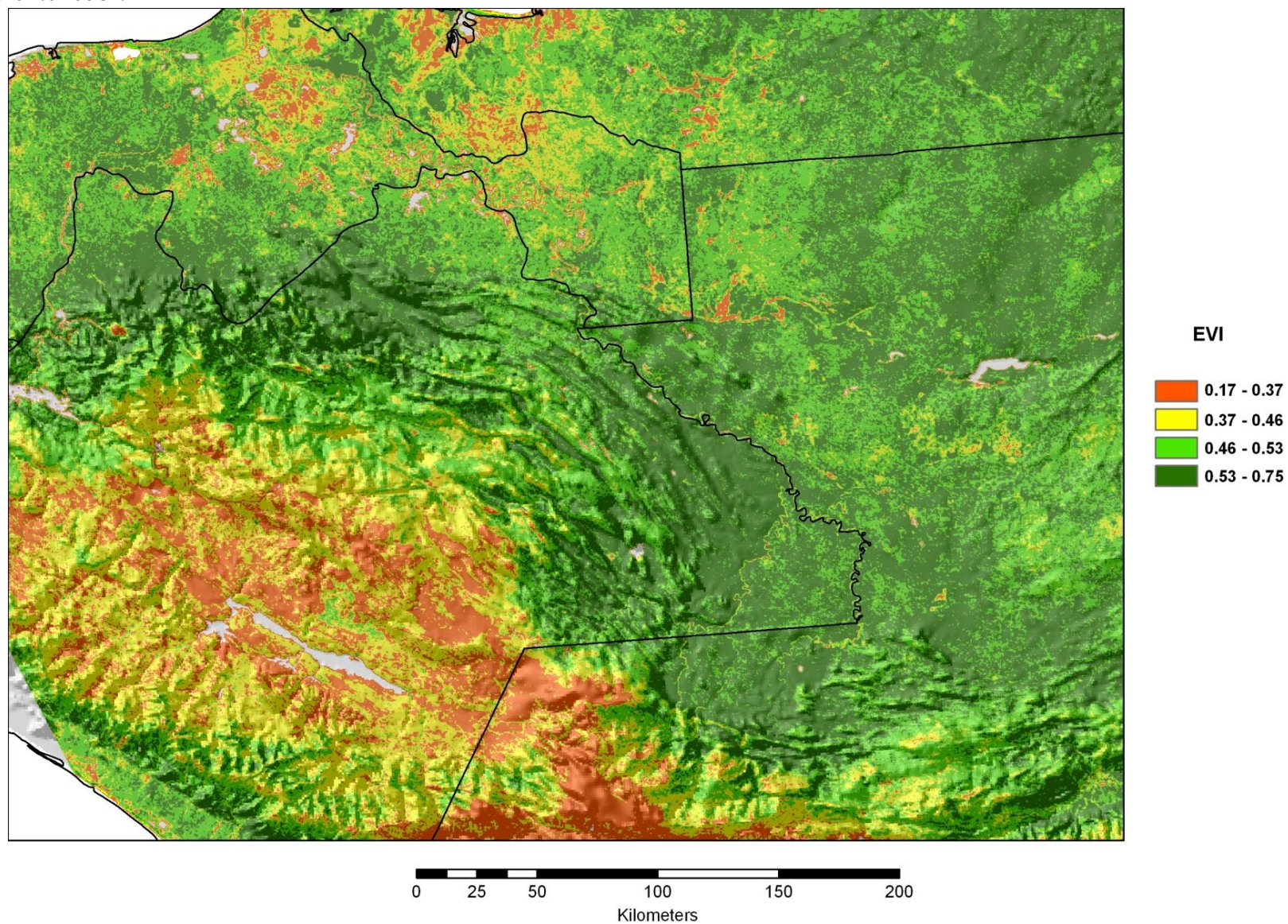
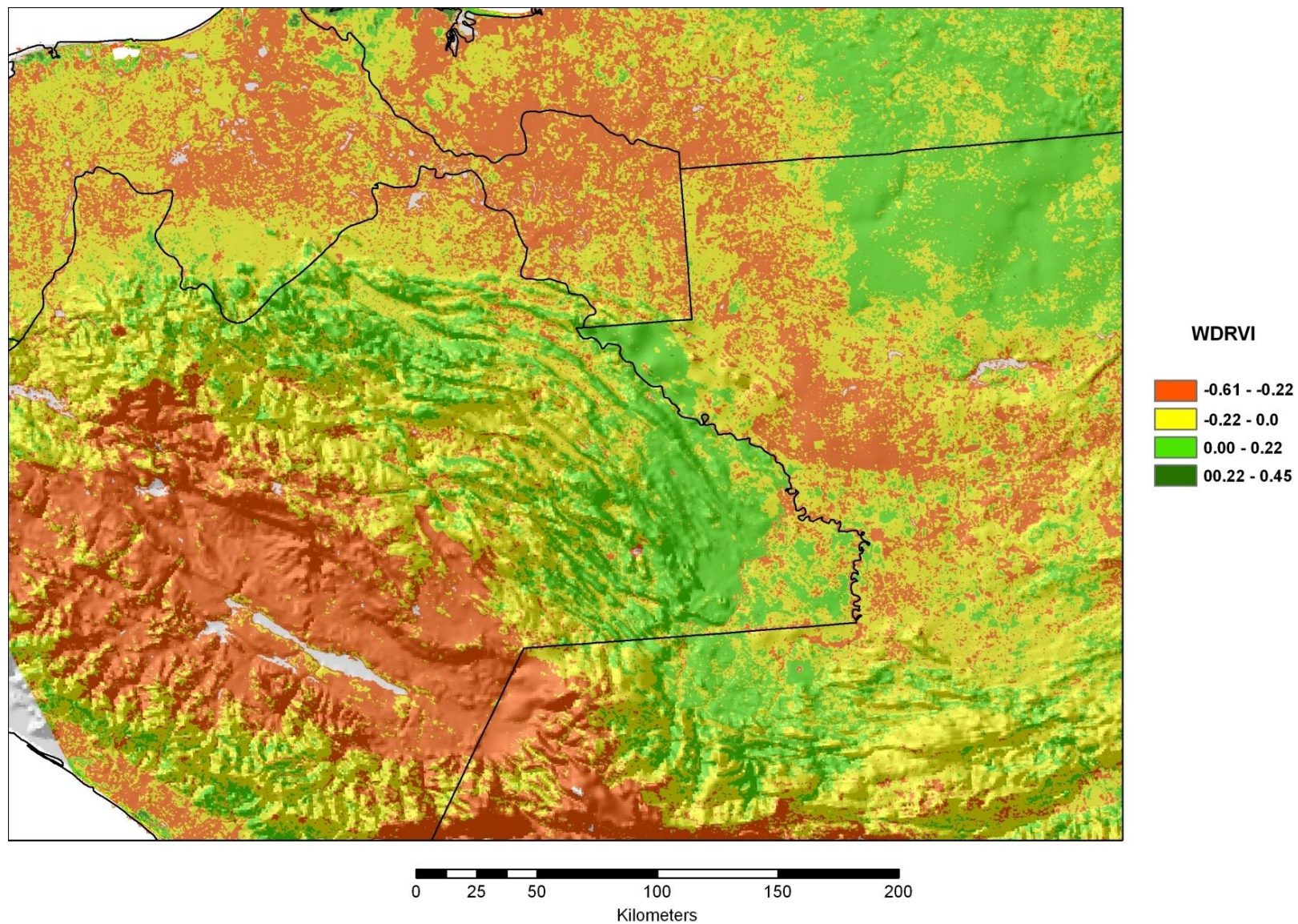


Figure 67. 2001 WDRVI a0 Fourier parameter. The Fourier a0 parameter is the arithmetic mean for the analyzed year and it is related to the overall greenness of a land cover type. High values are related to evergreen forests with less seasonal variations whereas low values are areas with more seasonal variation



The three indices show similar patterns to the vegetation type seasonality (see land cover/land use map in Figure 16) high values in areas with tropical rainforests and temperate forests cover types. Low values are seen in areas where the dominant cover types correspond to tropical deciduous forest and annual crops and grass/pasture (strong seasonality).

The graphs in Figure 68 show the 2001 to 2005 histograms for the three VI's a_0 Fourier parameter images used to demonstrate the overall variations for different years.

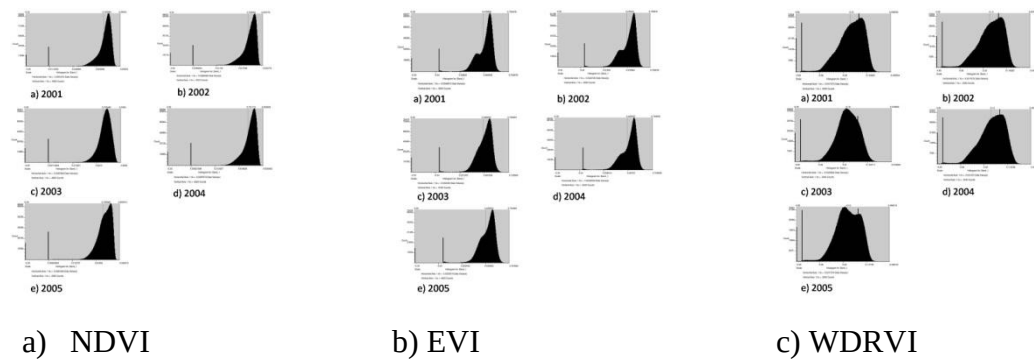


Figure 68. a_0 parameter image histogram for the NDVI (a) EVI (b) and WDRVI (c)

The most contrasting image is that showing the WDRVI compared with NDVI or EVI. Differences can be seen more clearly than with the other indices in areas covered by tropical rain forest and also in the valleys of the northern mountains of Chiapas where the deforestation process accounts for a substitution of forest cover by pastures. This is also evident in areas of recent colonization such as in the Mayan biosphere buffer zone and areas around Montes Azules and Sierra del Lacandón protected areas (Figure 17). The NDVI and EVI images look more homogeneous compared with the result of the WDRVI which shows a more heterogeneous pattern. This could be explained because the WDRVI

increases the range of the high values index, where the NDVI and the EVI saturate. The histograms from 2003 and 2005 are wider in particular in the WDRVI case. In both years the precipitation values shown in Table 10 and Table 12, were higher early in the rainy season (month of June) which may explain why those histograms are shifted to the left and are wider.

Table 13, shows another group of meteorological stations in the study area where June of 2005 was generally wetter than September. The year 2002 shows the normal condition where September is wetter than June (except at the Salto de Agua weather station).

	Station	June/02	Sept/02	June/05	Sept/05
1	Chicomuselo	193	328	371	348
2	Puente Concordia	147	359	287	149
3	Jaltenango	319	386	461	406
4	Angostura	219	242	307	175
5	Comitan	222	227	371	211
6	Lacantun	347	585	660	694
7	Zapata	223	185	359	245
8	Salto de Agua	677	447	725	551

Table 13. Comparison between rainfall (mm) of June and September 2002 and 2005 (Other stations in the study area)

5.2.2.2 Amplitude and Phase

As stated earlier, amplitude and phase images were built applying Equation 7 in a pixel by pixel matter for the five analyzed years using only the EVI. The results discussed in section 5.2.1 use land cover samples to show very small variations of amplitude values between years for the same land cover type even though this amount and distribution of

the precipitation were considerably different for those years. The illustrations from Figure 69 to Figure 73 show the spatial distribution of the amplitude values. The images were recoded in five ranges: lower values are related to low amplitude values which can resemble evergreen vegetation and high values means vegetation types similar to deciduous forest or annual crops which have a strong seasonality.

Most of the study area has values of very low to low; lowland areas covered mainly by tropical rain forest, tropical grasses and temperate forest in the mountain ranges (see land cover/Land use map Figure 16). Medium to high values are limited to the central depression of Chiapas and the pacific coast plain in the lower left part of the study area (see elevation and geomorphic map: Figure 11) and some extensive patches in the northern lowlands. This area corresponds in general to the tropical sub-humid conditions where vegetation types with strong seasonality are present except for the patches in the low lands. Vegetation types includes: tropical deciduous forest, annual crops and grass/pasture under strong dry/wet conditions and show more or less the same pattern year to year.

The spatial patterns of the first harmonic amplitude images are similar for the years 2001, 2002, and 2004 the last is the more homogeneous image dominated by low to very low values. 2003 and 2005 show more medium to high values in the lowlands and in some parts of the valleys between the mountain ranges (percentage of pixels from one category to another can reach 10% from one year to another). The very high amplitude values are in the Central Depression of Chiapas and also occasionally in some parts of the lowlands. Amplitude values change from one year to another, more variations from high to very high amplitude values occurs in years where total precipitation was higher

particularly early in the rainy season mostly in areas where are occupied by grass/pasture which are not the original vegetation cover and reflect a very complex dynamics. The areas with more dense and continuous vegetation show variations as well. Also values in areas where they would not be expected, could be indicators of drastic changes of the forest cover resulting by human management or intervention (forest clearing, burning, grazing) during those years. This method suggests can be used to detect drastic changes that could be interpreted as hot spots more susceptible to environmental variations, however extended and extensive field work or use of satellite data with better spatial resolution is needed in order to have a complete picture. The presence of high amplitude values in areas with high precipitation values where there is no strong seasonal component is expected.

Figure 69. Amplitude of the first harmonic 2001. Ranges are for low medium and high amplitudes. High amplitudes are related to vegetation types with strong seasonal component whereas low amplitude values are related to vegetation types with less seasonal component.

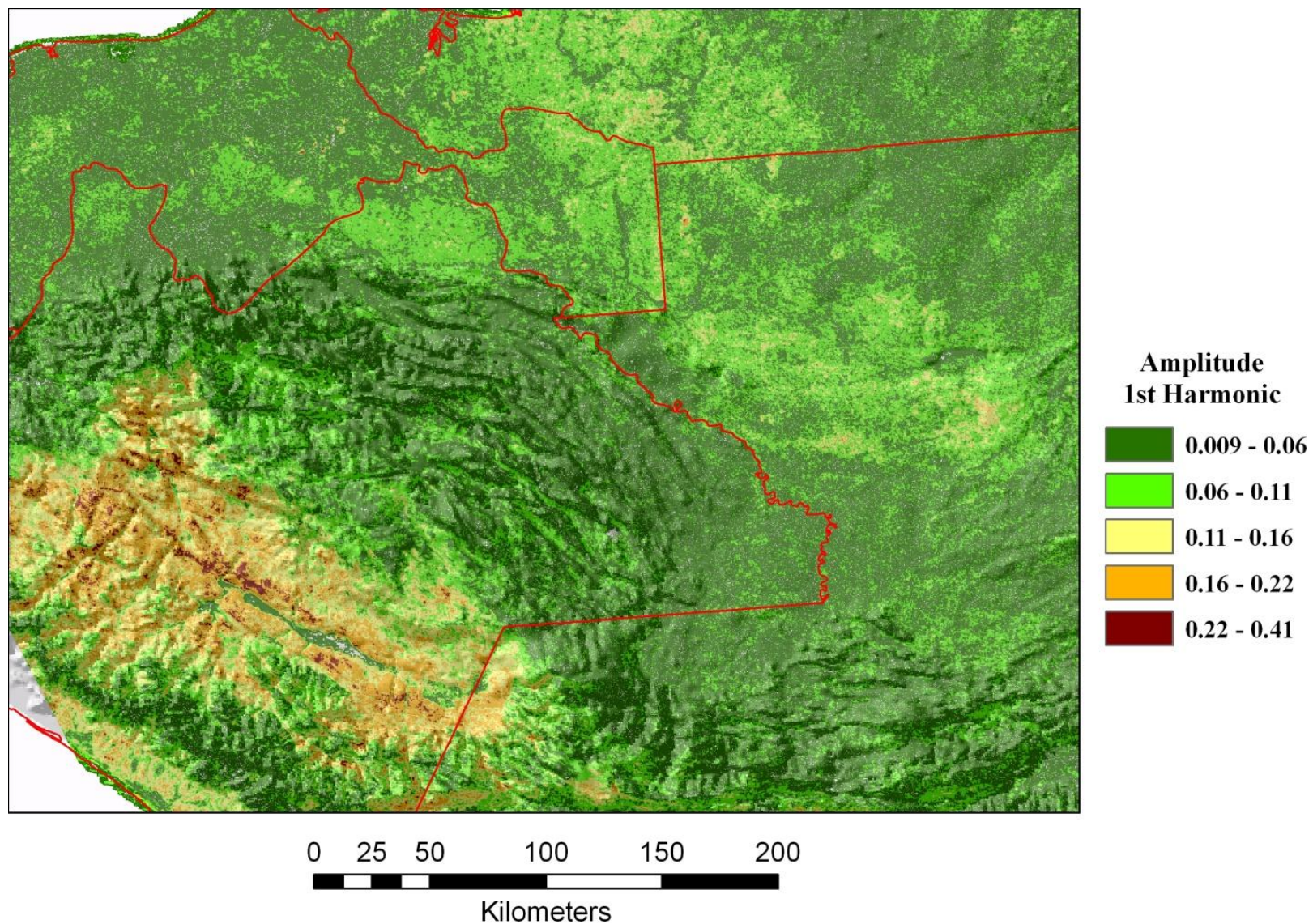


Figure 70. Amplitude of the first harmonic 2002. Ranges are for low medium and high amplitudes. High amplitudes are related to vegetation types with strong seasonal component whereas low amplitude values are related to vegetation types with less seasonal component.

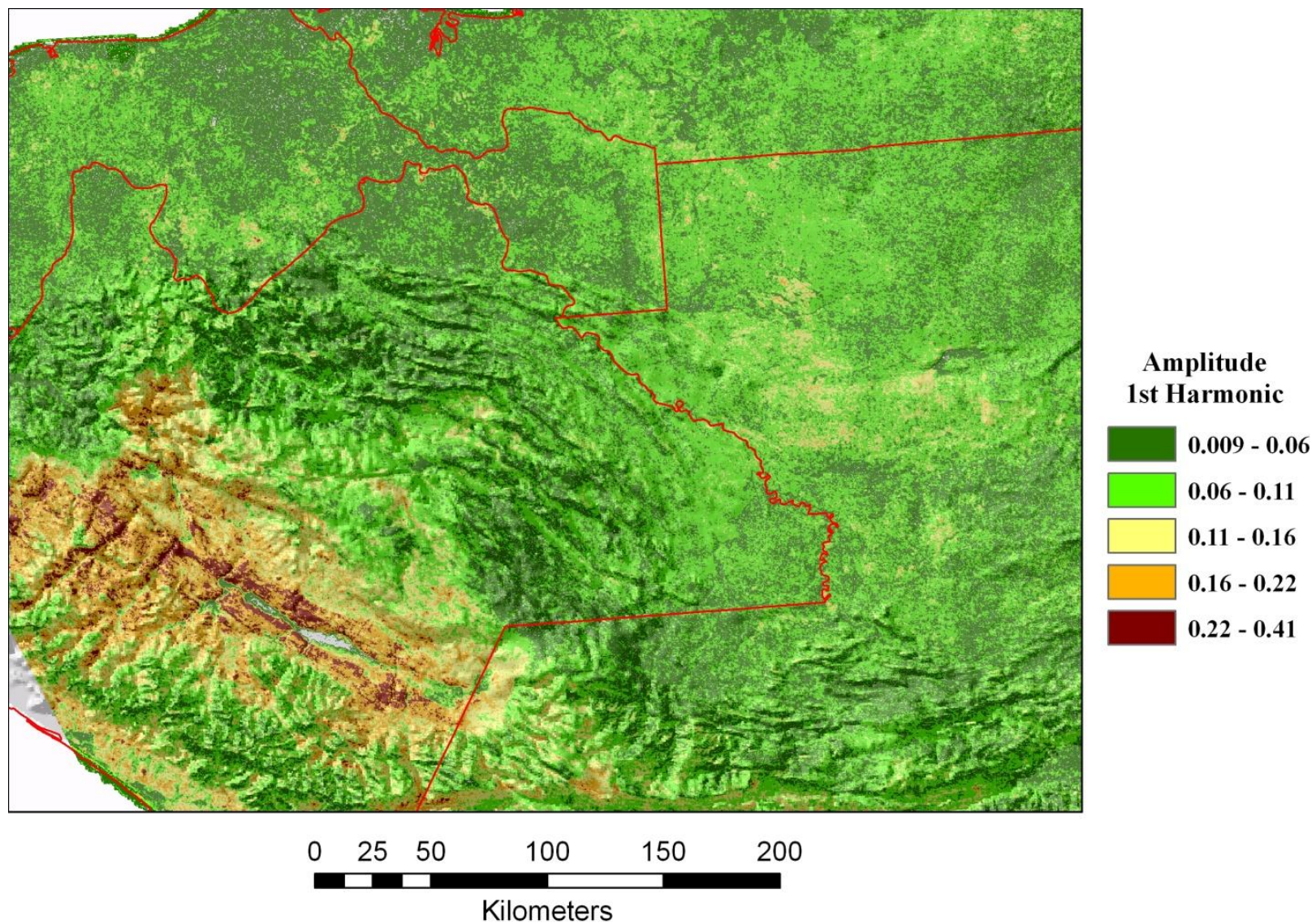


Figure 71. Amplitude of the first harmonic 2003. Ranges are for low medium and high amplitudes. High amplitudes are related to vegetation types with strong seasonal component whereas low amplitude values are related to vegetation types with less seasonal component.

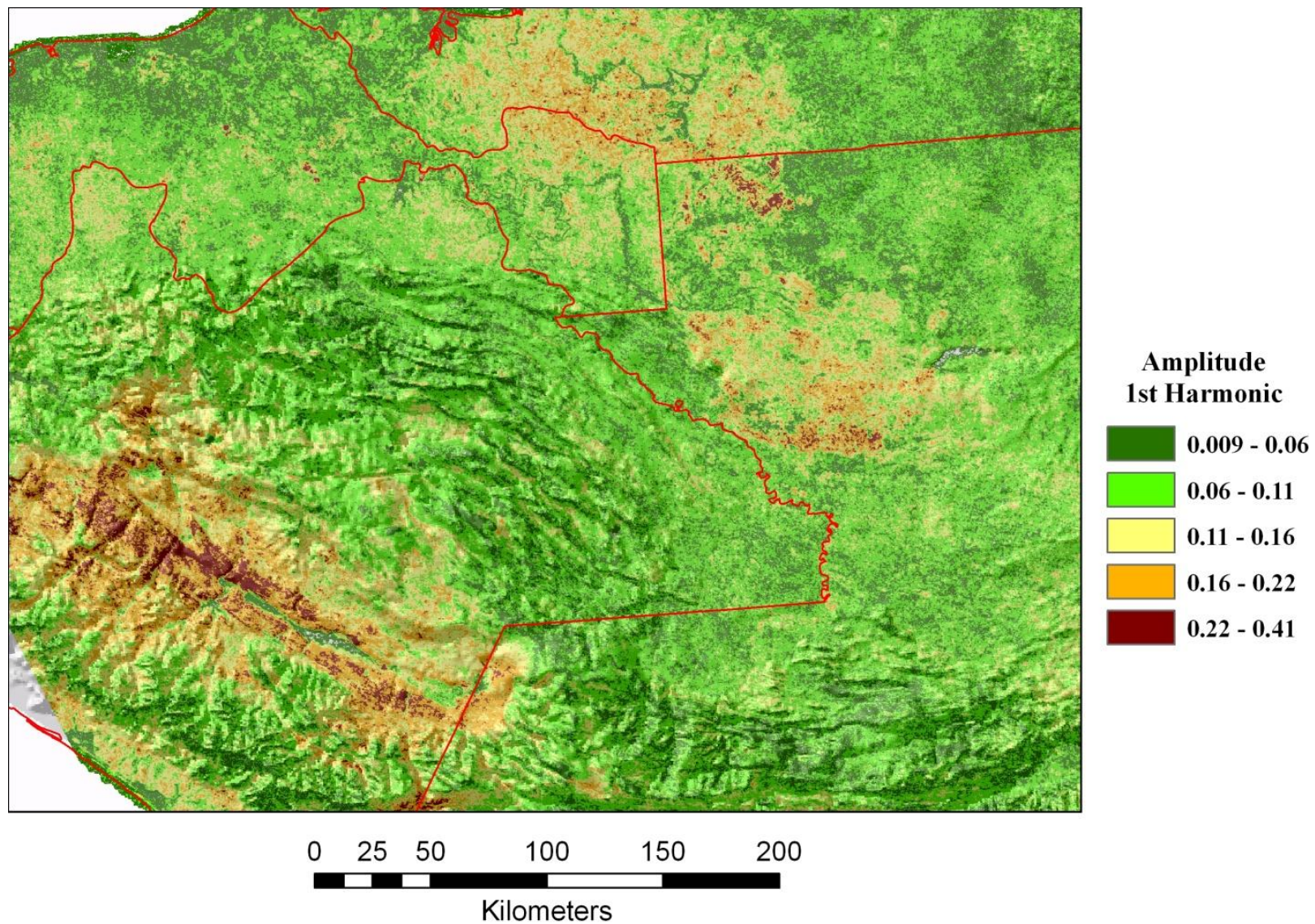


Figure 72. Amplitude of first harmonic for the year 2004. Ranges are for low medium and high amplitudes. High amplitudes are related to vegetation types with strong seasonal component whereas low amplitude values are related to vegetation types with less seasonal component.

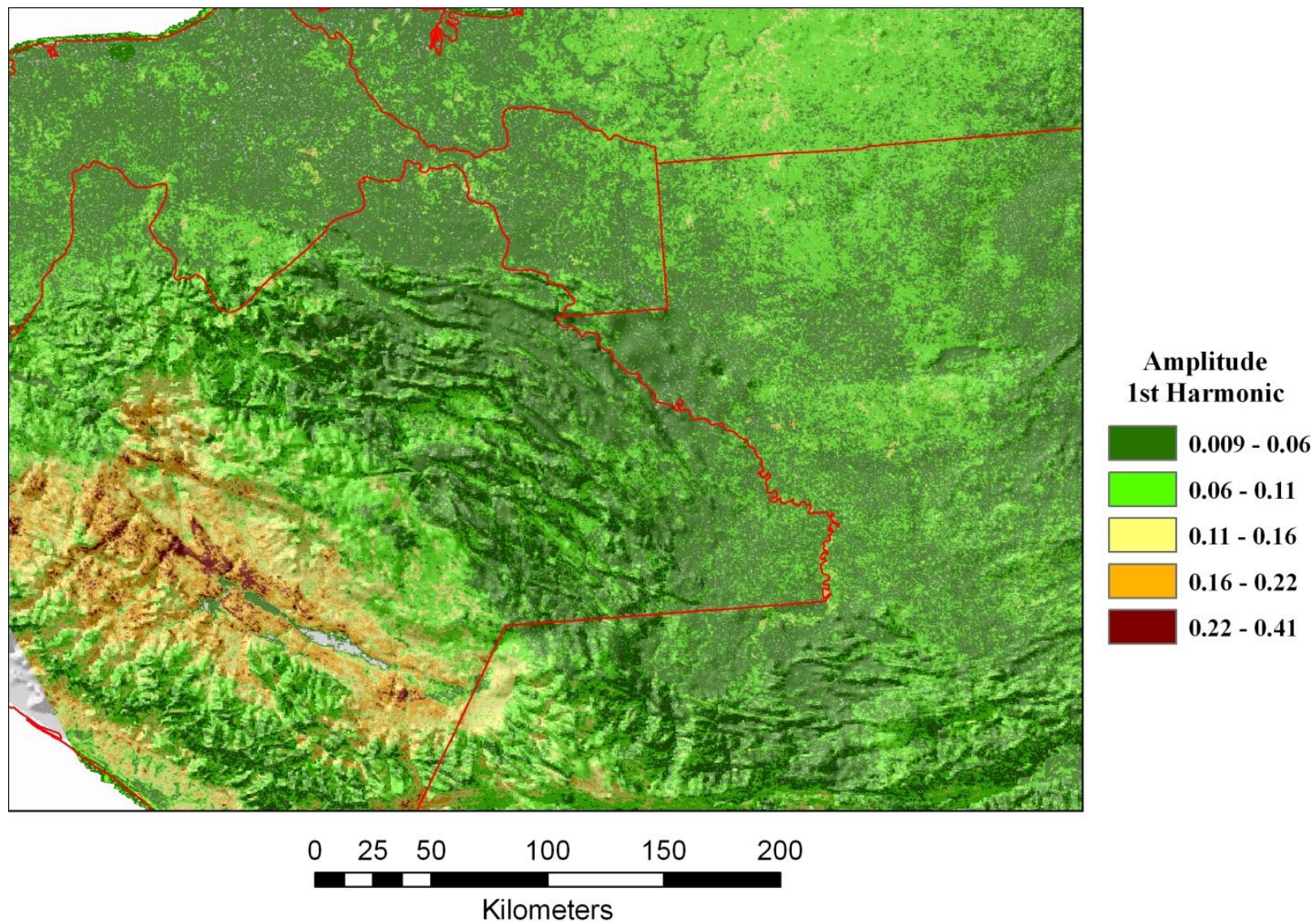


Figure 73. Amplitude of the first harmonic 2005. Ranges are for low medium and high amplitudes. High amplitudes are related to vegetation types with strong seasonal component whereas low amplitude values are related to vegetation types with less seasonal component.

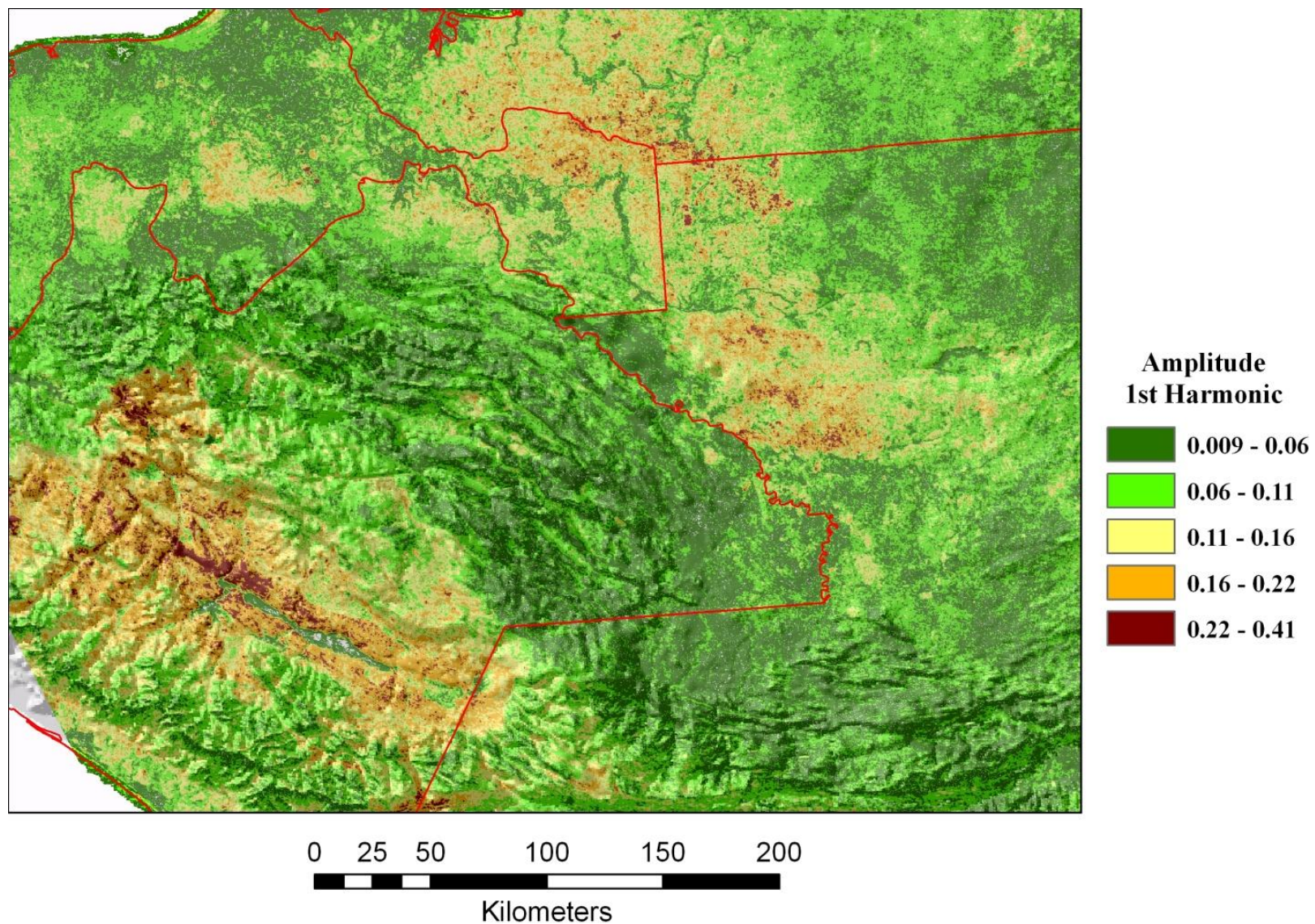


Figure 74 shows a comparison of the histograms of the phase images of the first harmonic. Note that results for 2005 have a different shape than other years and are generally shifted to the left with higher values around biweekly period 11. This difference may be explained by the same fact that 2005 was an extremely rainy year with especially high precipitation during the month of June. (See also precipitation values shown in Table 10, Table 12 and Table 13).

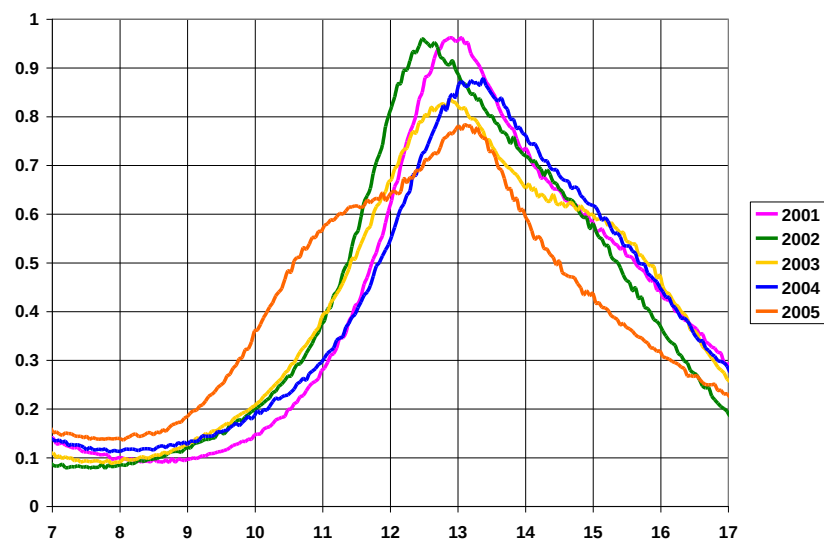


Figure 74. Histograms of the phase of the first harmonic images for the five analyzed years. Notice the shift to the left for the year 2005.

The annual phase images (Figure 75 to Figure 79), show the spatial variation of first harmonic phase values for years 2001 to 2005. Lower values are represented with reddish tones whereas higher values with greener tones. Grey tones are null values (pixels where the algorithm reach the maximum number of iterations and did not converge and may be related to remnant of cloudy pixels which were not completely filtered by the composite process nor eliminated by the smoothing process embedded in the Fourier series approximation procedure). As it was shown previously in the mean values (a_0

Fourier parameter) and in the histograms for the phase images (Figure 74) low phase values can be interpreted as early precipitation increment. There is considerable spatial variation for each year and between years. In general higher phase values are located in areas of temperate forests and continuous tropical forests (see Figure 16 land use/land cover map). Lower values are more frequent in areas of rain fed crops and grass/pasture. In the 2005 image the lower phase values are more frequent followed by 2003. Both years were characterized by an early precipitation regime compared with the rest of the years. Lower phase values are evident except in the Chiapas highlands and the northern part of the Petén lowlands (Figure 11).

Figure 75. Phase of the first harmonic 2001. Ranges are in biweekly period values. Lower values means shift to early biweekly periods and high values means shift to higher biweekly periods.

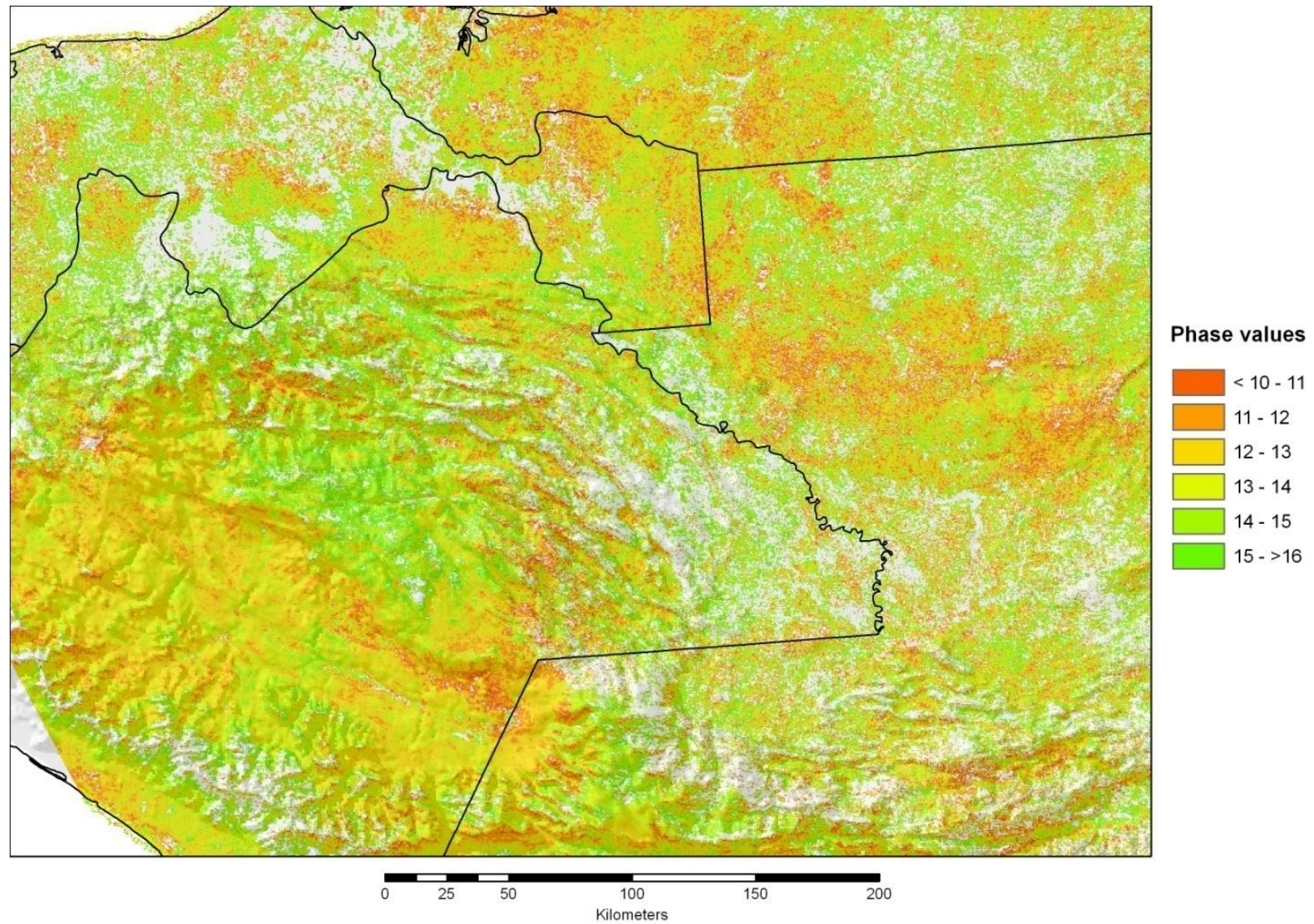


Figure 76. Phase of the first harmonic 2002. Ranges are in biweekly period values. Lower values means shift to early biweekly periods and high values means shift to higher biweekly periods.

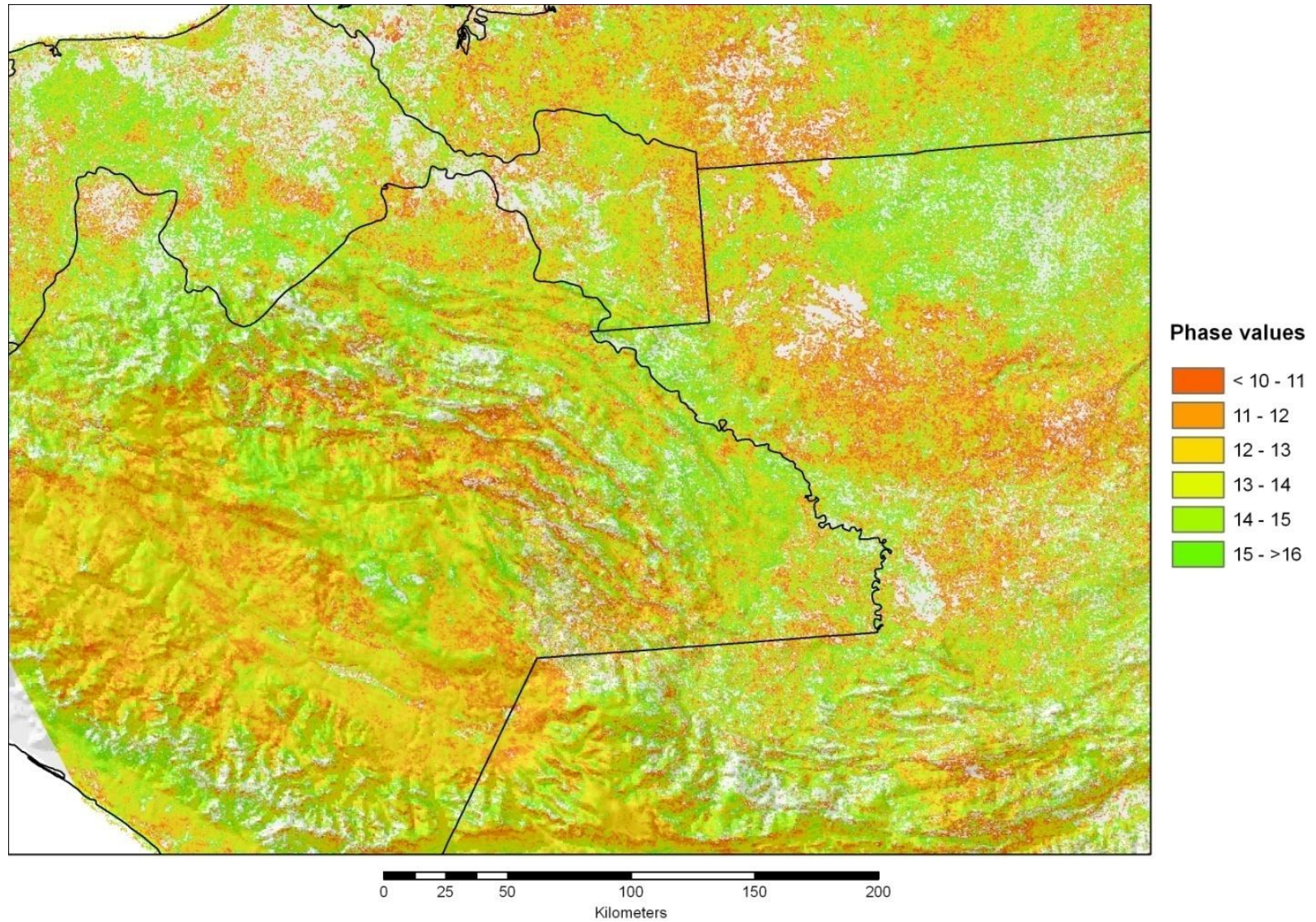


Figure 77. Phase of the first harmonic 2003. Ranges are in biweekly period values. Lower values means shift to early biweekly periods and high values means shift to higher biweekly periods.

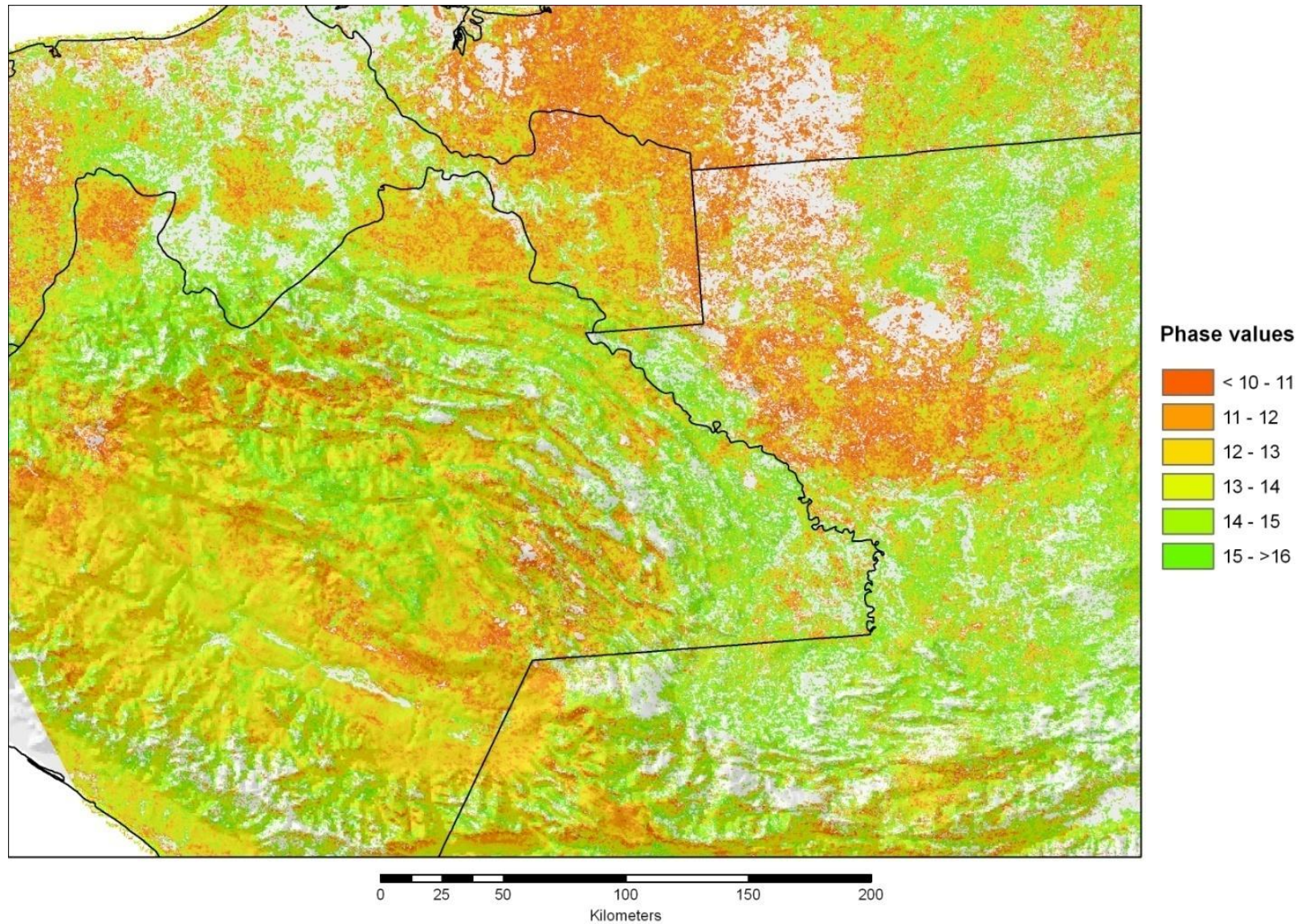


Figure 78. Phase of the first harmonic 2004. Ranges are in biweekly period values. Lower values means shift to early biweekly periods and high values means shift to higher biweekly periods.

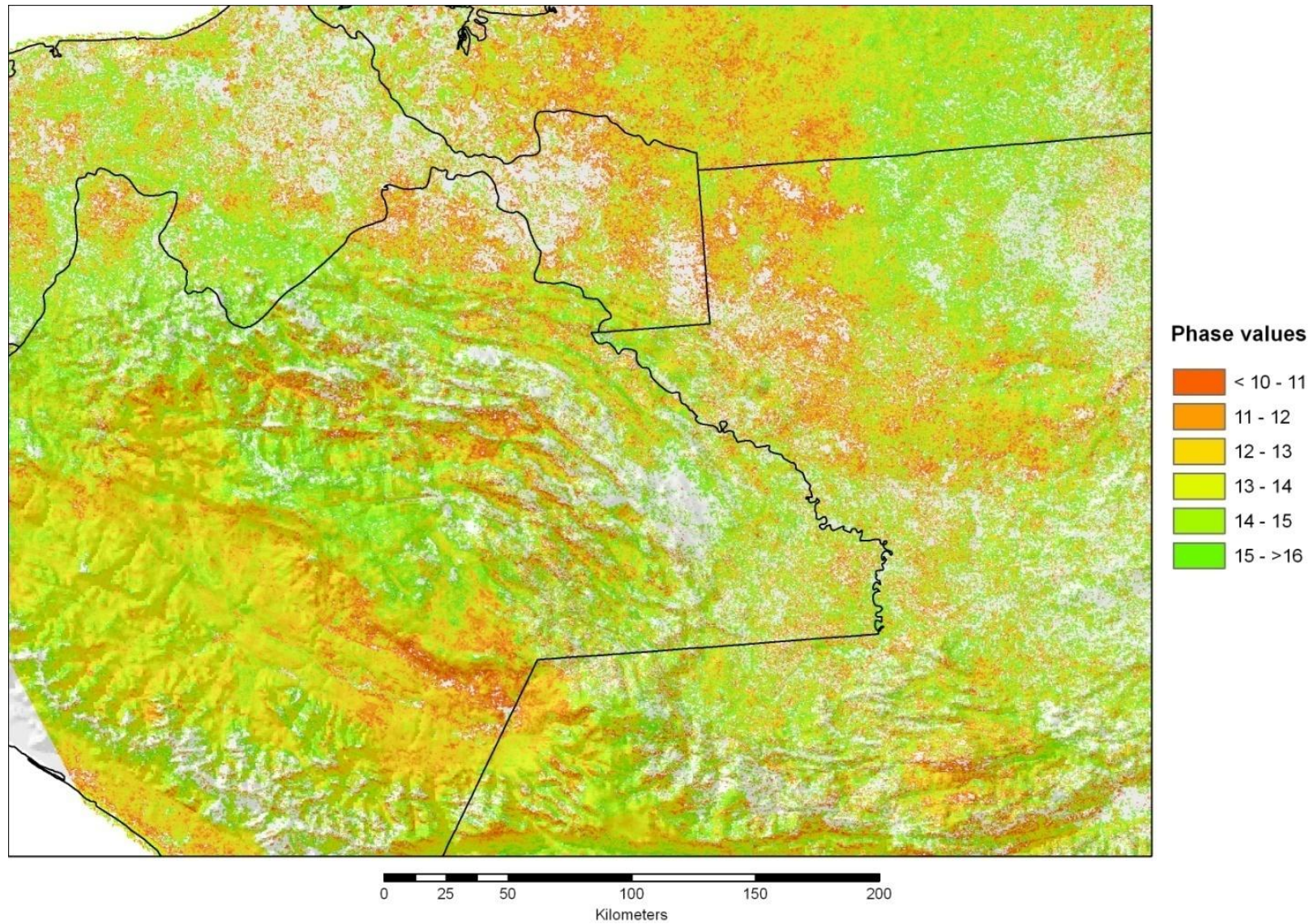
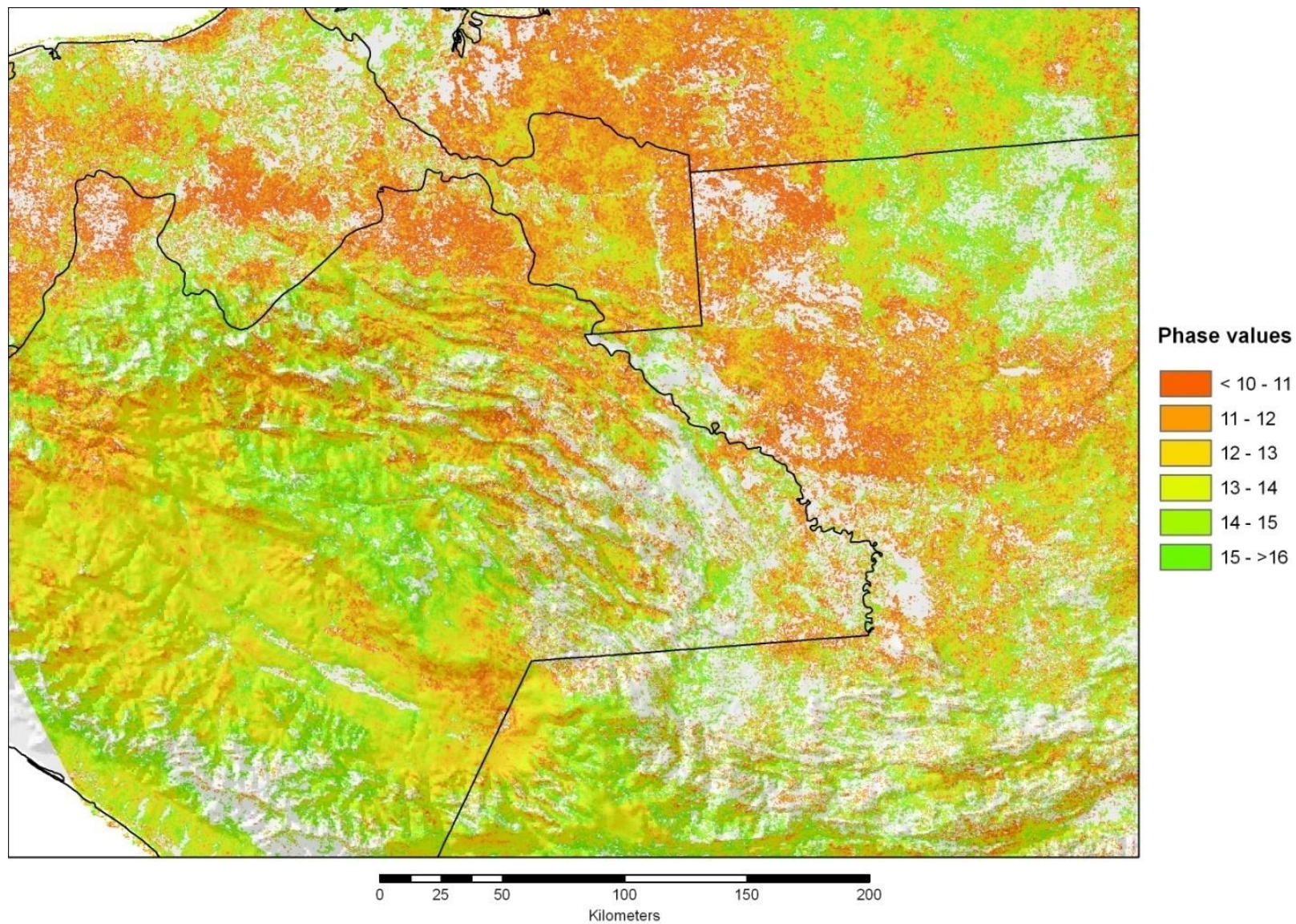


Figure 79. Phase of the first harmonic 2005. Ranges are in biweekly period values. Lower values means shift to early biweekly periods and high values means shift to higher biweekly periods.



First harmonic phase images also show variation between years. The extent of early phase values in the years 2003 and 2005 show changes located mainly in the lowlands a mosaic of grass/pasture and original vegetation remnants. It is likely that low phase values occur on slopes facing south which have lower precipitation.

5.2.3 Land cover/Land use Classification

The optimal Fourier parameters images calculated using Equation 7 were applied to the stack of twenty-three sixteen-day cloud-free MODIS 2001 composites. Data were used in an unsupervised classification in order to obtain a land use/land cover product based on seasonal characteristics of vegetation. The ISODATA clustering algorithm (Lillesand and Kiefer 1999) was used as a classifier. Classifications were made for the three VI's 2001 because it is the closest year to the date of the land use map (Figure 16) used as ground truth.

The maximum number of classes was set to twenty then clusters were grouped into five final classes: Class 1 was labeled as annual crops (corn and induced grasses in drier areas), class 2 as tropical deciduous forest, class 3 as grass/pasture (mainly tropical grasses), class 4 as temperate forest and class 5 as tropical rain forest. Percentages of the five classes relative to the total study area are shown in Table 14. Comparing the area of classes to the ground truth land use map NFI/CI (National Forest Inventory/Conservation International), the annual crops class was closest by the NDVI followed by the WDRVI and underestimated by the EVI. The deciduous forest class was overestimated (close to 1 percent) by the EVI and WDRVI and this class did not appear at all in the NDVI classification. Tropical grass and pasture class was overestimated by the NDVI and

WDRVI by more than two percent and 5 percent respectively and underestimated by 4 percent by the EVI classification.

	Class	NFI/CI	NDVI	EVI	WDRVI
	Non-Classified	1.9	2.0	0.9	1.0
1	Annual crops	8.8	8.9	4.3	8.6
2	Deciduous Forest	2.8	0.0	3.7	3.9
3	Grass/Pasture	34.6	36.8	29.9	41.1
4	Temperate Forest	15.5	3.9	17.0	9.3
5	Rain Forest	36.1	48.5	43.6	36.4
	Total %	100	100	100	100

Table 14. Surface percentages of the coverage of each class relative to the total surface of the study area

The temperate forest class was underestimated by the NDVI and WDRVI (12% and 6% respectively) and overestimated only by 2% by the EVI. The rain forest was overestimated by NDVI and EVI (12% and 7%) respectively and very closely estimated by WDRVI (less than 1%). The classification results are shown in the following figures:

Figure 80. Results of the 2001 NDVI unsupervised classification of the Fourier parameters grouped in six classes.

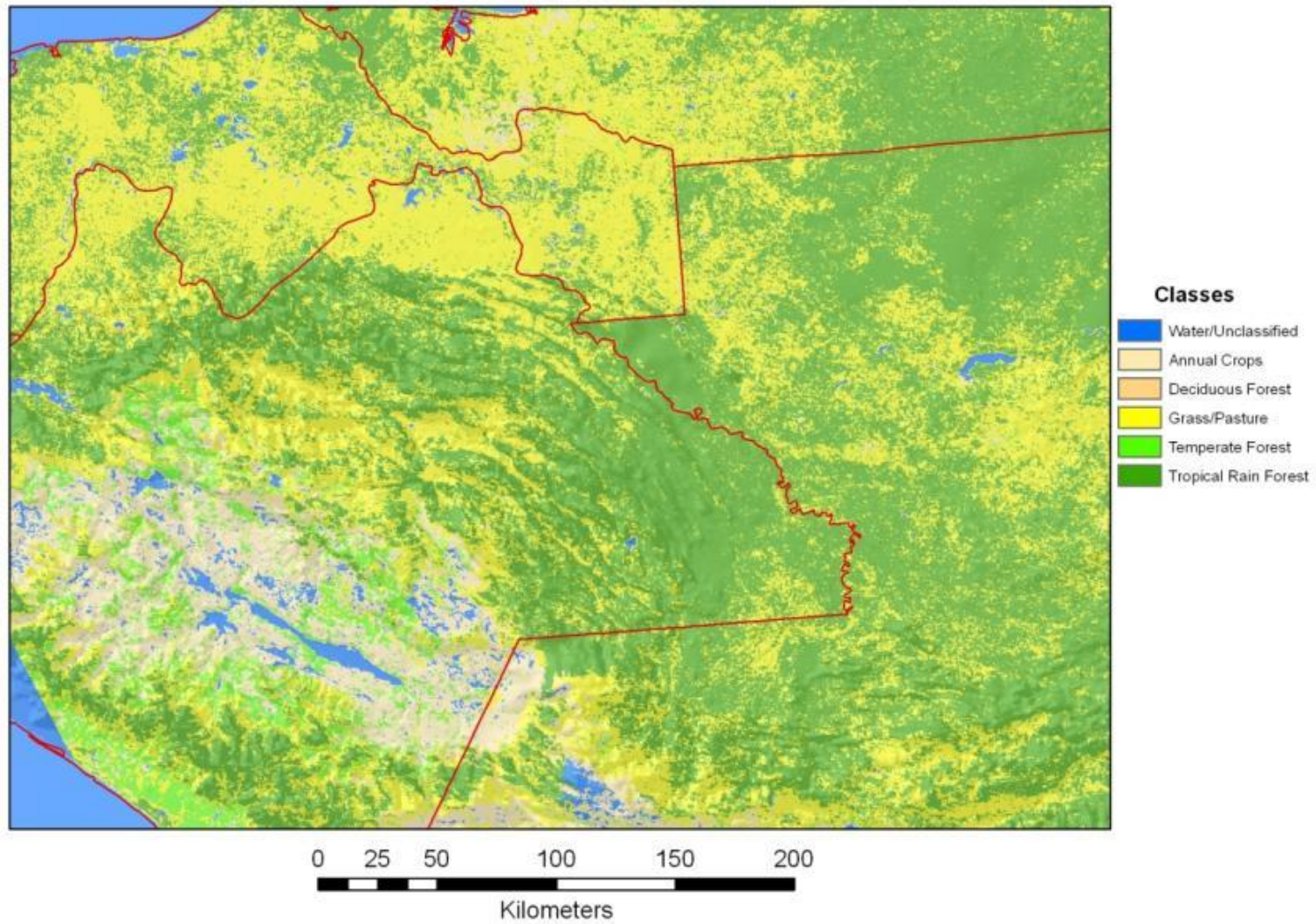
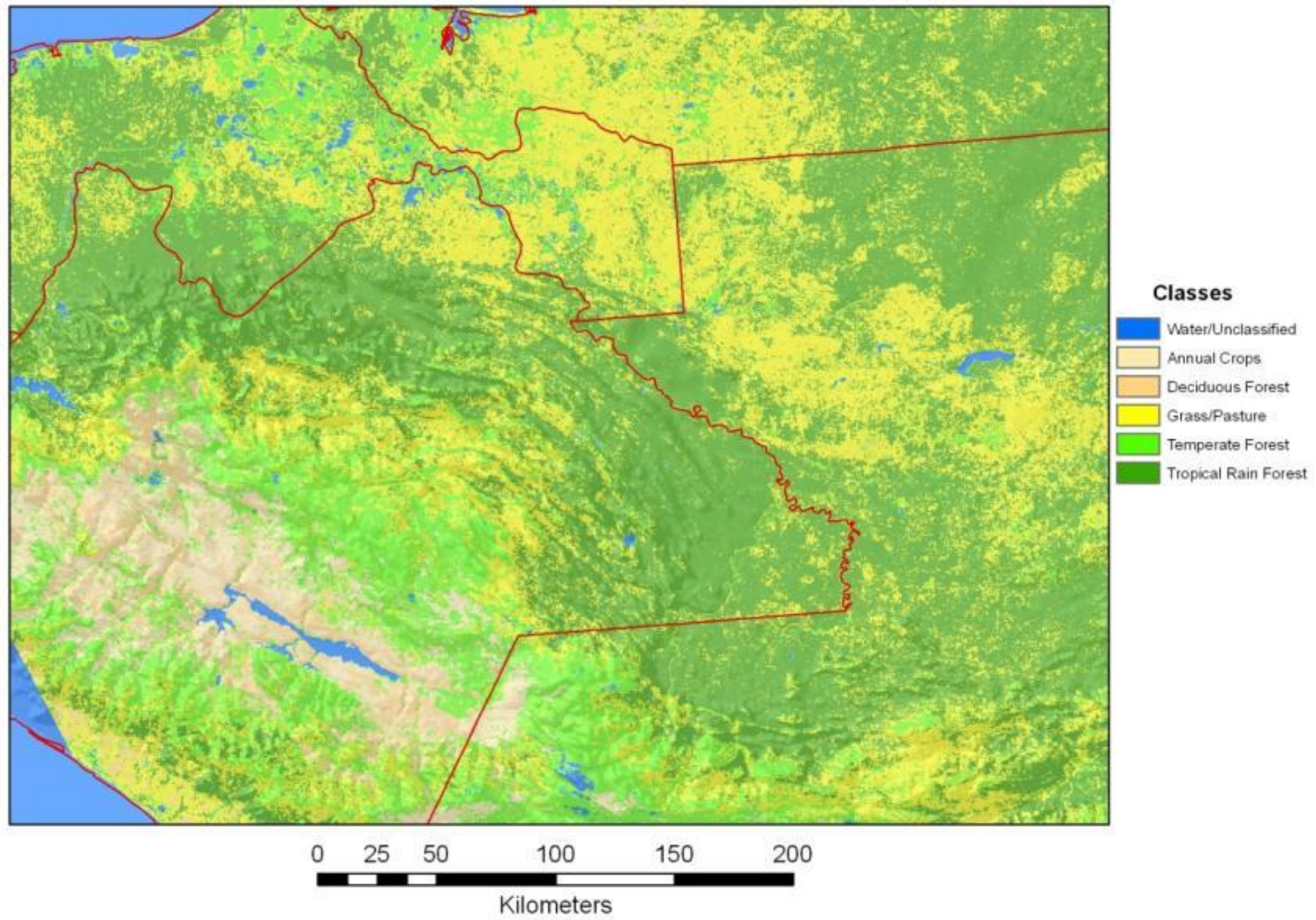


Figure 81. Results of the 2001 EVI unsupervised classification of the Fourier parameters grouped in six classes

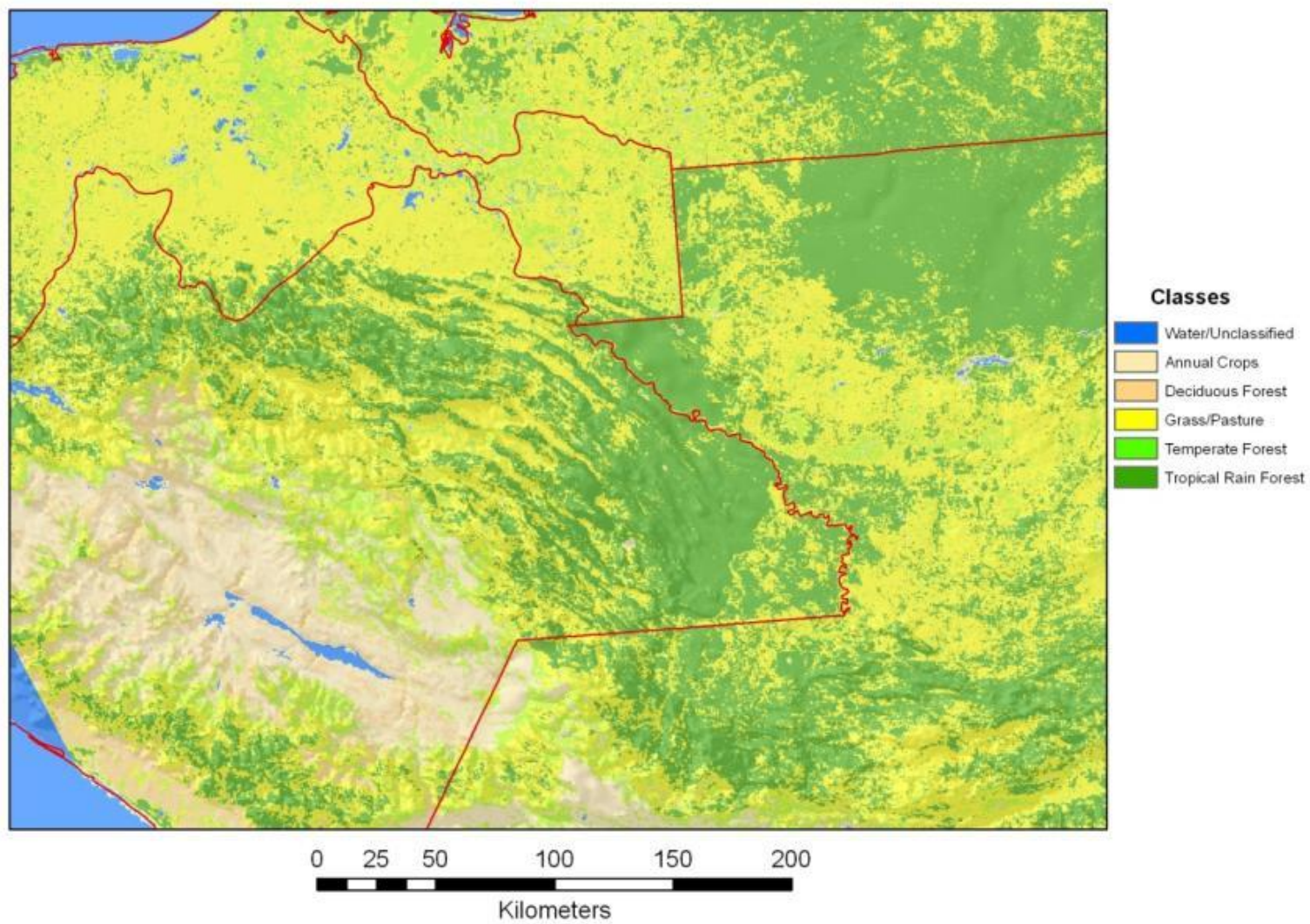


The spatial patterns of the classification correspond in general with the land use/land cover map. The NDVI classification was not able to pick the tropical deciduous forest class. The temperate forest is a very small class and there is no temperate class in the lowlands. The tropical grasses and tropical rain forest classes follow the same spatial pattern. In the case of the forest classes, the low performance of this index could be explained by the saturation of the index under high biomass conditions.

In the case of the 2001 EVI classification the first two classes are better defined, mostly located in the central depression of Chiapas. Class three which corresponds to temperate forest in the mountain ranges and palm trees in the lower lands are well defined. In this case, the tropical rain forest overestimation seems to be located mainly in the north-central part of the study area where the EVI classification shows an important area of vegetation contrasting with the land use map where it is more “patchy” related to isolated areas of tropical rain forest, dominated by tropical grasses.

The WDRVI classification generalizes class 1 over class 2. The temperate forest class is surrounded mainly by tropical grasses but is able to differentiate this class in the lower lands. Tropical grasses are well discriminated in the lower lands, but not in the higher lands (see the elevation map Figure 11). The tropical rain forest spatial pattern is very similar to the land use map.

Figure 82. Results of the 2001 WDRVI unsupervised classification of the Fourier parameters grouped in six classes.



5.2.3.1 Accuracy Assessment

For accuracy assessment purposes the land cover/land use map from the Mexican national forest inventory for the Mexican part and Conservation International land use map for Guatemala part was used as ground truth (Figure 16). Over this map a set of 2000 random points were sampled. Simple random sampling was used. To select n sample units out of N units in the population, such that every one of the possible distinct samples has an equal chance of being selected (Congalton 1988). The land use and classification class values were obtained for each point from the sample in order to build error matrices for each classification (NDVI, EVI and WDRVI) for each of the index error matrices. Accuracy totals and kappa statistics tables were built, and overall accuracy and overall kappa statistics reported.

The NDVI classification found only 4 out of the 5 classes. Class 1 (annual crops) is confused with tropical grasses and it has a similar producer's/user's accuracy around 36%. Class 4 (temperate forest) has also a very low accuracy (less than 10% user's and 33% producer's accuracy). This class is mainly mixed with the grass/pasture class. The classes that perform better in this case are class 3 (grass/pasture) with around 50% in producer's/user's accuracy and class 5 with 77% of producer's accuracy and 57% user's accuracy. The user's accuracies are a measure of the commission errors which result when one incorrectly identifies pixels associated with a class as other classes, or when one improperly separates a single class into two or more classes. The producer's accuracies are the errors of *omission* which occur whenever the user simply does not recognize pixels that should have identified as belonging to a particular class (Lillesand and Kieffer 2000). Both classes are difficult to distinguish among them and are less

proportional with class 4. They have similar temporal behavior and therefore are difficult to discriminate. The overall classification accuracy is low (60%). There are very low kappa statistics by class as well as low overall kappa statistics (less than 5%).

CLASSIFIED DATA	REFERENCE DATA						ROW TOTAL
	0	1	2	3	4	5	
0 Unclassified	350	6	1	6	2	1	366
1 Annual Crops	3	50	16	47	16	2	134
2 Deciduous Forest	0	0	0	0	0	0	0
3 Grass/Pasture	9	44	6	309	113	131	612
4 Temperate Forest	1	10	12	23	24	1	71
5 Rain Forest	9	29	4	186	119	470	817
Column Total	372	139	39	571	274	605	

Table 15. Error Matrix. accuracy assessment of the 2001 NDVI unsupervised classification

Class Name	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	Users Accuracy
0 Unclassified	372	366	350	---	---
1 Annual Crops	139	134	50	35.97%	37.31%
2 Deciduous Forest	39	0	0	---	---
3 Grass/Pasture	571	612	309	54.12%	50.49%
4 Temperate Forest	274	71	24	8.76%	33.80%
5 Rain Forest	605	817	470	77.69%	57.53%
Totals	2000	2000	1203		

Table 16. Accuracy Totals 2001 NDVI unsupervised classification

Class Name	Kappa
0 Unclassified	0.9463
1 Annual Crops	0.3263
2 Deciduous Forest	0
3 Grass/Pasture	0.3071
4 Temperate Forest	0.2329
5 Rain Forest	0.3911

Table 17. Conditional Kappa by category 2001 NDVI unsupervised classification

The EVI classification separates the five classes. Most have low accuracy (less than 50%) except for the tropical rain forest class and grass and pasture which has a user's accuracy close to 50% (Table 18). Annual crops are confused mainly with the grass/pasture class and this class has a very low producers/users accuracy (23% and 39% respectively). Tropical deciduous forest (class 2) is confused with annual crops, grass/pasture and even with temperate forest reaching a producer's/user's accuracy of 43% and 29%. Temperate forest is around 44% in both cases and is a class confused with grass/pasture and tropical rain forest. Grass and pasture class has producers/users accuracy of 43% and 49% respectively and is confused mainly with class 5 which has the highest accuracy (68% producer's 56% user's) of all the five classes. The overall classification accuracy is 59%. The *kappa* class statistics values are shown in Table 20 and overall *kappa* is very low (less than 0.5).

CLASSIFIED DATA	REFERENCE DATA						ROW TOTAL
	0	1	2	3	4	5	
0 Unclassified	353	0	0	2	3	2	360
1 Annual Crops	0	32	10	30	8	2	82
2 Deciduous Forest	1	14	17	15	11	0	58
3 Grass/Pasture	8	32	2	245	73	138	498
4 Temperate Forest	8	28	6	63	123	51	279
5 Rain Forest	2	33	4	216	56	412	723
COLUMN TOTAL	372	139	39	571	274	605	

Table 18. Error Matrix. Accuracy assessment of the 2001 EVI unsupervised classification

Class Name	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	Users Accuracy
0 Unclassified	372	360	353	---	---
1 Annual Crops	139	82	32	23.02%	39.02%
2 Deciduous Forest	39	58	17	43.59%	29.31%
3 Grass/Pasture	571	498	245	42.91%	49.20%
4 Temperate Forest	274	279	123	44.89%	44.09%
5 Rain Forest	605	723	412	68.10%	56.98%
Totals	2000	2000	1182		

Table 19. Accuracy Totals 2001 EVI unsupervised classification

Class Name	Kappa
0 Unclassified	0.9761
1 Annual Crops	0.3447
2 Deciduous Forest	0.279
3 Grass/Pasture	0.289
4 Temperate Forest	0.3521
5 Rain Forest	0.3833

Table 20. Conditional Kappa by category 2001 EVI unsupervised classification

The accuracy results for the WDRVI classification are shown in the following tables. Similar to the previous cases, annual crops, tropical deciduous forest and temperate forest classes have very low accuracy similar to the values obtained for the EVI. The performance for the grass/pasture class is lower than the EVI but higher in the case of class 5 (tropical rain forest) this index outscores the other two dramatically with percentages in producer's/user's accuracy greater than 70%. The overall classification accuracy is higher 63.4%, as well as the overall *kappa* and *kappa* statistics for the tropical rainforest class (0.51 and 0.59) respectively. A summary of the overall accuracy and overall kappa are given in Table 24.

CLASSIFIED DATA	REFERENCE DATA						ROW TOTAL
	0	1	2	3	4	5	
0 Unclassified	345	0	0	2	3	1	351
1 Annual Crops	11	49	14	40	9	2	125
2 Deciduous Forest	0	10	18	27	14	4	73
3 Grass/Pasture	11	48	3	360	118	157	697
4 Temperate Forest	4	20	2	50	65	10	151
5 Rain Forest	1	12	2	92	65	431	603
Column Total	372	139	39	571	274	605	

Table 21. Error Matrix. accuracy assessment of the 2001 WDRVI unsupervised classification

Class Name	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	Users Accuracy
0 Unclassified	372	351	345	---	---
1 Annual Crops	139	125	49	35.25%	39.20%
2 Deciduous Forest	39	73	18	46.15%	24.66%
3 Grass/Pasture	571	697	360	63.05%	51.65%
4 Temperate Forest	274	151	65	23.72%	43.05%
5 Rain Forest	605	603	431	71.24%	71.48%
Totals	2000	2000	1268		

Table 22. Accuracy Totals 2001 WDRVI unsupervised classification

Class Name	Kappa
0 Unclassified	0.979
1 Annual Crops	0.3466
2 Deciduous Forest	0.2316
3 Grass/Pasture	0.3233
4 Temperate Forest	0.3401
5 Rain Forest	0.5911

Table 23. Conditional Kappa by category 2001 WDRVI unsupervised classification

	NDVI	EVI	WDRVI
Overall Accuracy	60.15	59.1	63.4
Overall Kappa	0.465	0.464	0.5192

Table 24. Overall accuracy and overall kappa for the three indices

Several authors have applied variations of harmonic analysis to land cover classification. For example, Jakubauskas et al. (2002) applied AVHRR to crop identification in the United States Great Plains and reported 52% overall accuracy with the highest of 72% for the grass class. Xinfang et al. (2004) carried out forest classification in Northeast China to separate non-forest, evergreen, deciduous forest and shrub but did not report the accuracy. Andres, Salas and Skole (1994) in Brazil grouped in three broad classes but no accuracy value is reported. Geerken, Zaitchik and Evans (2005) in Syria, reported a overall accuracy of 73% and Moody and Johnson (2001) in southern California compare the classification against the USGS-EDC Land cover map and the Boston University land cover of North America (reporting an overall accuracy of 53% with the EDC map and 46% with the BU map).

Compared with such previous studies, the results of the present work are very good. The three indices have similar results, however the overall accuracy of the WDRVI and particularly, the high accuracy of this index for the rainforest class, make the use of this particular index very promising in land use/land cover change in Mesoamerica.

References

- Andres, L., W. Salas, and D. Skole. 1994. Fourier analysis of multi-temporal AVHRR data applied to a land cover classification. *International Journal of Remote Sensing* 15(5):1115-1121.
- Brown, J., W. Jepson, J. Kastens, B. Wardlow, J. Lomas, and K. Price. 2007. Multitemporal, Moderate-Spatial-Resolution Remote Sensing of Modern Agricultural Production and Land Modification in the Brazilian Amazon. *GIScience & Remote Sensing* 44(2):117-148.
- Congalton, R. 1988. A comparison of sampling schemes used in generating error matrices for assessing the accuracy of maps generated from remotely sensed data. *Photogrammetric Engineering & Remote Sensing* 54(5):593-600.
- ENVI/IDL. [4.0]. USA, Research Systems, Inc.
- Geerken, R., B. Zaitchik, and J.P. Evans. 2005. Classifying rangeland vegetation type and coverage from NDVI time series using Fourier Filtered Cycle Similarity. *International Journal of Remote Sensing* 26(24):5535-5554.
- Jakubauskas, M.E., Legates D.R., and J.H. Kastens. 2002. Crop identification using harmonic analysis of time-series AVHRR NDVI data. *Computers and Electronics in Agriculture* 37:127-139.
- Lillesand, T.M. and R.W.Kiefer. 2000. *Remote Sensing and Image Interpretation*. John Wiley & Sons, Inc: USA.
- Loyarte, M.M.G. and M. Menenti. 2008. Impact of rainfall anomalies on Fourier parameters of NDVI time series of northwestern Argentina. *International Journal of Remote Sensing* 29(4):1125-1152.

- Moody, A. and D.M. Johnson. 2001. Land-Surface Phenologies from AVHRR Using the Discrete Fourier Transform. *Remote Sensing of Environment* 75(3):305-323.
- Ratana, P. and A. Huete. Seasonal dynamics of native and converted cerrado physiognomies with MODIS data. Geoscience and Remote Sensing Symposium, 2004. IGARSS '04. Proceedings. 2004 IEEE International. Geoscience and Remote Sensing Symposium, 2004.IGARSS '04.Proceedings.2004 IEEE International 6, 4336-4339. 2004.
- Torrence, C. and G.P. Compo. 1998. A Practical Guide to Wavelet Analysis. *Bulletin of the American Meteorological Society* 79(1):61.
- Viña, A., G.M. Henebry, and A.A. Gitelson. 2004. Satellite Monitoring of Vegetation Dynamics: Sensitivity Enhancement by the Wide Dynamic Range Vegetation Index. *Geophysical Research Letters* 31.
- Wardlow, B.D., S.L. Egbert, and J.H. Kastens. 2007. Analysis of time-series MODIS 250m vegetation index data for crop classification in the U.S. Central Great Plains. *Remote Sensing of Environment* 108(3):290-310.
- Xinfang, Y., Z. Dafang, C. Hua, and H. Xiyong. Forest classification based on MODIS time series and vegetation phenology. Geoscience and Remote Sensing Symposium, 2004. IGARSS '04. Proceedings. 2004 IEEE International. Geoscience and Remote Sensing Symposium, 2004.IGARSS '04.Proceedings.2004 IEEE International 4, 2369-2372. 9-20-2004.

Chapter 6 Conclusions and recommendations for further research

6.1 Summary

Analysis and monitoring of humid tropical areas still represents a challenge from the remote sensing point of view. Presence of clouds, high humidity, high biomass and the particular dynamics of the land cover of such areas are important limiting factors. Anthropogenic activities that modify the dynamics of these areas make analysis more complex. Because the importance of tropical vegetation in the carbon cycle and the high population pressures which impact forests, it is very important to have better methods to evaluate and monitoring tropical forests. Multitemporal remote sensing used as time series of vegetation indices can be used to assess behavior of vegetation. This work contributes to development of monitoring of tropical regions using vegetation indices. This research demonstrated that tropical regions particularly tropical rain forests have seasonal changes in greenness detectable by MODIS.

6.1.1 Vegetation Indices Comparison

Three VI's (NDVI, EVI and WDRVI) were compared and analyzed for different land cover types and environmental conditions. Despite the fact that the Pearson correlation between the indices and precipitation data was low and not significantly different (0.45 for the NDVI, 0.56 for the EVI, 0.48 for the WDRVI, in the case of tropical deciduous forest) and very low for the cases of tropical rainforest, the EVI showed better relationship with precipitation data and shows clear annual periods

(seasonality) according to the wavelets analysis. It is particularly important that the performance of the WDRVI in the land cover classification was much better. The classification using the WDRVI was higher overall (63%) compared with the other indices (60% for the NDVI and 59% for the EVI) and particularly in tropical rainforest and grass/pasture delineation (71% for tropical rain forest and around 60% for pasture). These are two of the main classes in the study area and in general in tropical regions since it is a common practice that areas of tropical rain forest are converted to pasture. Another advantage of the use of the WDRVI is that it can be derived from the same bands used to calculate the NDVI. The other two indices tend to overestimate the tropical rainforest area and considering that the NDVI is the most commonly used index, the NDVI should be used carefully. However it is important to consider that the indices may be reporting different things. The EVI is more related to vegetation structure whereas NDVI and WDRVI more related to greenness.

6.1.2 Fourier Parameters Meaning

The core of the analysis was the application of the Fourier series approximation method. The method is a very powerful and flexible procedure which provided important information about vegetation temporal behavior related to water availability. The impact of the amount and distribution of rainfall were revealed by the Fourier parameters obtained (mean VI, first harmonic amplitude and first harmonic phase), more important, the images obtained show the spatial variation of those changes at better spatial resolution each year and between years.

The a_0 or mean value (which can be obtained by other methods as well) provided overall information about the response of vegetation for a particular year. The images resulting from this analysis show differences among the VI's. Differences are more evident in the two of the analyzed years, also important results from the comparison of histograms for the different years indicate variations related in this case to the increased amount of precipitation early in the rainy season (month of June) in the study area for the years 2003 and 2005.

First harmonic amplitude images show the main annual component for each pixel. High values are related to strong seasonal component. Besides the areas where a high amplitude value is expected due to the presence of vegetation types such as the tropical deciduous forest or annual crops areas, there are isolated areas in the lowlands which have medium to medium-high amplitude values. These areas increased drastically in the year 2003 and particularly in 2005 which are the years with more amount and especially early precipitation. What can be concluded is that these areas are very sensitive to changes in the precipitation pattern.

The phase value of the first harmonic (time of the peak of the amplitude of the first harmonic) was found to also have implications of the response of vegetation to changes in the precipitation. The value of this parameter shifted to the left from 15 (biweekly period) to 14 in the case of tropical deciduous forest and from 14 to 11 in the tropical rain forest case. The extreme left-value corresponds to the year 2005 where the amount of precipitation was higher in the month of June. Changes in the precipitation regime can have important effects in the response of vegetation to the remaining time (growing season) which is important in terms of the ecosystem functionality or adaptation

to natural variations which is not homogeneous. The first harmonic phase images can be used together with the mean value and amplitude images to explain the temporal variations of vegetation response to climatic changes in larger areas.

Multitemporal vegetation analysis using the MODIS EVI and results from the Fourier series method, provide a comprehensive picture of the land surface intra-annual e inter-annual variations, characterizing the vegetation cycles even in tropical forests where the seasonality is subtle. The method is able to detect variations in extensive and continuous tropical rain forests but most important shows that areas originally cover by tropical rainforest and converted to pastures or a mixture of forest remnants and pastures are highly sensitive to climatic variations. However due to the complexity of the region more research is needed in order to determine the driving factors of change. Variations can reflect differences in vegetation density, biomass productivity, albedo, or evapotranspiration, which are key elements in ecosystem dynamics and also important to energy budget calculations and as variables in numerical weather prediction models.

6.2 Recommendations for Future Research

Mapping tropical regions and the spatio-temporal relationship of satellite derived VI's and climate at regional scales are major research subjects explored in this work. The results obtained shows that tropical regions and particularly tropical rain forests have intra and inter-annual variability which need to be taken in account. The methods used here decompose the temporal response of vegetation into few key components in a simple way which can be used to explain and characterize the landscape variability. Future research must include:

Uses of longer time series (more than ten years of MODIS data are already available). With longer time series more inter and intra-annual variability is expected which can bring different conditions (i.e. late rain, changes of intensity of the MSD, presence of the ENSO among others) and consequently expect different vegetation responses. Also the method can be applied to longer periods (two years or more). By doing this it is expected that variations could avoiding the lack of enough points in the annual data that may hiding this variations. The availability of eight days MODIS 500m product has to be tested as well.

Detailed analysis of higher harmonics (2nd and higher), can also lead researchers to evaluate three months or one half month components. These components can be related also to changes in intensity of the MSD or extraordinary precipitations during the dry season.

Explore methods to differentiate the nature of the changes (natural or man-made). Here in this work it seems that changes in the volume and distribution of precipitation impact extensive areas and apparently the man-made changes are hidden. The possibility to

characterize the type of change can lead to understand better the particular dynamics of those areas.

There are approaches tested in semi-arid conditions which include the calculation of anomalies or departures of the mean. Apply this type of methods in tropical environments can also provide valuable information of the dynamics of the ecosystem, also complementary with the basic statistics of the time series such as the variance, standard deviation, skewness.

Finally to test the methods proposed in this work in other tropical areas under different physical and human conditions.