# UNDERSTANDING LARGE AREA TROPICAL FOREST PHENOLOGY USING REMOTELY SENSED AND GROUND DATA SOURCES

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## ABSTRACT

## UNDERSTANDING LARGE AREA TROPICAL FOREST PHENOLOGY USING REMOTELY SENSED AND GROUND DATA SOURCES SIMON JONES (1998)

Remotely sensed (spectral) phenological data has often been used to characterise and investigate tropical forest ecosystems. The basic assumptions, linking real (biological) and remotely sensed (spectral) phenology, have however rarely been scrutinised and little empirical information from synchronous datasets exists.

This research selected three tropical vegetation communities; each characterised by a different climate, biological phenology and each hypothesised to exhibit a differing spectral phenology. An extensive verification campaign was then initiated to collect phenological data from all three of these sites for an entire phenological cycle. The verification dataset comprised; forest structural parameters, meteorological measurements, litterfall weights, phenological observations (of leaf flushing, senescence and abscission), quantifications of canopy openness and LAI (using hemispherical photography and Ceptometry) and overpass-synchronous radiometry readings.

Large area (1 km<sup>2</sup>), remotely sensed spectral data was then acquired, for all sites, from the NOAA-14 AVHRR and ERS-2 ATSR-2 satellite sensor systems. An evaluation of the biological significance of the spectral phenological data was then undertaken using two basic methodologies. First, the ground verification data were compared to several commonly used spectral vegetation indices. Next, textural changes, in the spectral landscape, attributed to each verification site were assessed. At two of the monitored sites, spectral phenology was shown to have a strong physiological basis at the scale of the vegetation community. This was attributed to, the pronounced seasonality in the climate at these locations, and, the relative structural simplicity of the vegetation formations. At the third site (a structurally more complex, seasonally-inundated tropical forest) the association between biological and spectral phenology was less conclusive. Clearly further work is required before the scientific community can be certain that all temporal trends, derived from 1km spatial resolution image data, are providing accurate insights into the biological processes, of humid tropical forests, but in general the association between spectral and biological phenology is a strong one.

### **Key Words:**

## **REMOTE SENSING, TROPICAL FORESTS, MONITORING, PHENOLOGY, SEASONALITY, GROUND SURVEY & VERIFICATION TECHNIQUES, MULTI-TEMPORAL DATASETS**

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# **0.8 SYMBOLS AND ABBREVIATIONS**

Systeme Internationale (SI) units have been used in preference to all others. The only exceptions to this are the use of litres and millilitres, instead of the proper  $dm^3$  and  $cm^3$ .

а	Foliage area density $(m^2 m^3)$ ; albedo, reflectance (dimensionless).
a(z)	Foliage area density function $(m^2 \text{ per } m^3)$
a s 1	above sea level
AVHRR	Advanced Very High Resolution Radiometer
ATSR-2	Along Track Scanning Radiometer Version-2
AWS	Automatic Weather Station
BD-0	Bi-Directional-o Reflectance
BISE	Best Index Slone Extraction
BOLFOR	Provecto de Maneio Forestal Sostenible Ministerio de Desarrollo
DOLIOR	Sostenible y Medio Ambiente, Santa Cruz, Bolivia
d	Diameter (m).
dbh	diameter at breast height
Di	Julian date (days).
EMR	Electro Magnetic Radiation
EO	Earth Observation
ERS-2	Second Earth Resources Satellite
ESA	European Space Agency
FOV	Field of View
GAC	Global Area Coverage
GPS	Ground Control Point / Global Positioning System
GVI	Global Vegetation Indices
h	Hour angle of the sun (degree or radian).
h	Planck's constant (6.626 * $10^{-34}$ J s).
h	Relative humidity (dimensionless).
h	Height, thickness (m).
h	Hour.
ha	Hectare (= $10^4 \text{ m}^2$ ).
I	Irradiance (W $m^{-2}$ or mol $m^{-2} s^{-1}$ ).
IT	Information Technology
ITCZ	Inter-tropical convergence zone
К	Kelvin (Units)
LAC	Large Area Coverage
LAI	Leaf area index; area of foliage per unit ground area (unitless)
meanVC	mean Value Composite
MVC	Maximum Value Composite
NDVI	Normalised Difference Vegetation Index
NIR	Near Infrared
NOAA	National Oceanic and Atmospheric Administration
PCA	Principal Component Analysis
RMS	Root Mean Square (errors)
r	Radius (m).
SAVI	Soil Adjusted Vegetation Index
Т	Temperature (K; °C).
T <sub>(a)</sub>	Air
TF	Tropical Forest
TM	Thematic Mapper
T <sub>(w)</sub>	Wet, wet bulb.

Wet bulb temperature (K; °C).
Time.
Wind speed (m s <sup>-1</sup> ). $$
Volume (m <sup>3</sup> ).
Vegetation Indices
simulation of the satellite signal in the solar spectrum (Tanré et al.,
1990)
absorbity (dimensionless).
Declination (degrees or radians).
Emissivity (dimensionless).
Solar azimuth (degrees).
Leaf azimuth (degrees).
Wavelenth of light (nm; µm).
Latitude (degree or radian).
Latitude (°)
Solar zenith angle (°)
Inclination of leaf to the horizontal (degrees).
Reflection coefficient or reflectance (dimensionless).
Stefan-Boltzmann constant (= $5.67 \times 10^{-8}$ W m <sup>-2</sup> K <sup>-4</sup> ); standard deviation.
Transmissivity (%)

# CHAPTER 1 INTRODUCTION

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## CHAPTER 1 INTRODUCTION

#### **1.1 RESEARCH CONTEXT**

This investigation was conceived and realised at the end of the twentieth century, an era characterised by both an information technology (IT) revolution and a global inertia of responses to the imperative environmental and social issues this exposed. One of the more compelling enigmas, that the IT revolution has revealed, concerns the anthropogenic impact on the world's biomes. The ever increasing demands of sedentary civilisation, for renewable and non-renewable natural resources, has placed pressures on the global environment that are both more widespread and more destructive than has previously been assumed. Although this issue is a highly favoured topic for international conferences, politician's sound-bytes and even PhD theses, little progress has been made tackling the key issues of equity, biodiversity and sustainability. Centre stage, in terms of the rhetorical debate, are the tropics (particularly the humid tropics) since it is here that many of the Earth's poor, the majority of the world's plant and animal species and the last significant areas of commercially exploitable land are to be found. The technological innovations that have facilitated our comprehension of these global problems include amongst them satellite earth observation (EO). EO technology has enabled the extent (and changes in extent) of natural resources to be quantified, and has aided in the analysis of their degradation. Paradoxically, the same technology has also been used as a tool for their more efficient exploitation and destruction.

Since this research is set within the humid tropical biome, and, as EO is an integral part of the research methodology, two research agendas could be appropriate. The first is firmly embedded in the scientific paradigm, juxtaposed between the disciplines of ecology and EO science. The second agenda is a socio-political-environmental one. This study will focus exclusively on the scientific; the methodology adopted for this investigation is therefore unashamedly empirical.

### **1.2 CONCEPTUAL AND THEORETICAL BASE**

This section introduces the core issues and themes of this investigation; tropical forest (TF) phenology is defined and the various dimensions of the research outlined.

At the centre of this study is an examination of the relationship between remotely sensed or 'spectral' phenology and ecosystem or 'biological' phenology. The origins of the word *phenology* are in the Greek  $\Pi\eta\alpha$ tvo meaning appearance. As an ecological concept, phenology has been in use for almost 200 years (Von Humboldt, 1805) today assuming the general definition of '...the seasonal sequence, duration and timing of lifecycle events throughout the year', Packman and Harding pp.23 (1982). Spectral phenology, as defined within the remote sensing paradigm, is the quantification of the timing, duration and intensity of photosynthetic activity alone (Lloyd, 1990; Defries and Townshend, 1994). This difference occurs since it is only the botanical components, of a living landscape, that undergo seasonal changes profound enough to be monitored from space. Justice *et al.* (1985) note, however, that phenology is generally accepted as including not only the timing of recurring biological events but also their causes, especially with regard to meteorological phenomena.

### **1.2.1** Phenological studies of tropical forest ecosystems

Within this investigation, the association between spectral and biological phenology is examined in the context of TF environments. Studies of TF biological phenology are common in the botanical literature (Table 1.1). Most, however, are concerned only with the fruiting, flushing and flowering events of an individual species or a family. Typically, observations are only carried out on a handful of specimens. As a consequence, any comparison between biological phenological observations and remotely sensed data does not easily allow quantitative associations to be tested (although they are often inferred). This is since remotely sensed data (at any spatial resolution) represents an integration of many and diverse TF reflectance components.

Author(s)	Scale of Ecological Observation
Adis et al. (1979); Anderson (1955); Araujo (1970); Beniwal (1987); Borchert (1980); (1992); Bullock and Solismagallanes (1990); Cornforth (1970); Duke (1990); Ewusie (1968); Fournier-O (1974); (1976); Fournier-O et al. (1986); Ghate and Kumbhojkar (1991); Gordon et al. (1974); Hernandez-Gil (1987); Hopp (1974); Jackson (1966); Jackson (1978); Koelmeyer (1959); Kunkel-Westphal and Kunkel (1979); Ledezma Arias (1993); Lowman (1992); Monasterio and Sarmiento (1976); Newstrome et al. (1994); Njoku (1963); Rundel and Becker (1987); Umano-Dodero (1988)	Species
Alencar et al. (1979); Alvim and Alvim (1978); Bierregaard et al. (1992); Bionski and Fowler (1989); Boaler (1966); Brokow (1982); Catinot (1970); Collins (1977); Daubenmire (1972); Frankie et al. (1974); Gammon and Carter (1979); Hopkins (1966); Hopkins and Graham (1989); Klinge (1977); Lam and Dudgeon (1985); Lambert et al. (1980); Leigh et al. (1982); Lieberman (1982); Malaisse (1974); Malaisse and Malaisse-Moisset (1970); Martinez-Yrizar and Sarukhan (1990); Medway (1972); Morellato (1992); Murali and Sukumar (1993); Ng (1981); Prasad and Hedge (1986); Puig and Delobeille (1988); Putz (1979); Raich (1989); Ralhan et al. (1985a); (1985b); Reich and Borchert (1984); Singh and Singh (1992); Singh et al. (1990); Spain (1984); Tanner (1980); Taylor (1974); Van Schaik (1986); Vermura (1994); Wright and Cornejo (1990)	Community
Bray and Gorham (1964); Cruz Alencar et al. (1979); Flemming and Partridge (1984); Lonsdale (1988); Sarmiento and Monasterio (1983)	Ecosystem

 Table 1.1
 Botanical observations of tropical forest phenology

### **1.2.1.1 Biological phenology**

A common perception of TFs is that they are evergreen; indeed that all TFs are the archetypal *tropical rain forests*. In fact, almost all tropical environments exhibit seasonal variations in abiotic resources. Temperature, humidity, rainfall and day-length (although the amplitude of the last may be small) being the more obvious seasonally-varying environmental parameters. All these variables may potentially then play a role in tropical vegetation phenological processes. Indeed, botanical phenological stratagem may be seen in terms of competition for abiotic resources (such as light and water); whereby lifecycle events have evolved to take advantage of opportunities for exploiting these resources (Lieberman, 1982). Since seasonality may expose TF vegetation to regular periodic changes in the quality and abundance of these resources, TF formations may exhibit phenological cycles in tandem or lagged to the dynamics of these abiotic variables. However, two complicating factors exist within TF ecosystems; namely that:

(i) the seasonality of the abiotic variables is complex and in some cases minimal; and

 (ii) plant species diversity within TFs is potentially very high, the number of tree species per hectare often exceeding 100 (Longman and Jeník, 1987). This high species diversity may imply a high phenological diversity within a given area.

Consequently, a TF formation may contain many distinct phenological stages simultaneously.

#### 1.2.1.2 Spectral phenology

Within the humid tropics, vegetation reflectance dominates the remotely-sensed spectral signal (at all wavelengths  $< 2.5 \mu m$ ). EO data have often been used to infer the magnitude and extent of botanical variables such as the projected leaf area per unit ground area (LAI) and above-ground biomass (e.g. Lillesand and Kiefler, 1987; Justice et al., 1989; Asrar et al., 1989; Achard and Blasco, 1990; Pinty and Verstraete, 1992; Derrien et al., 1992; Lambin and Strahler, 1994a; 1994b; Millington et al., 1994; Myneni et al., 1997). The techniques most commonly used to derive these estimations are based around the use of spectral vegetation indices (principally the NDVI). Differing within-image illumination and viewing conditions, and the often low ground-sample to pixel-size ratio cause many inconsistencies in the use of spectral reflectance products. Derived vegetation indices are sensitive to changes in: soil reflectance (Huete et al., 1992), atmospheric effects (Pinty and Verstraete, 1992), sun-sensor geometry (Qi et al., 1994) and sensor characteristics (Elvidge and Chen, 1995). These inconsistencies aside, most analyses equate a constant high vegetation index, throughout the year, as indicative of an evergreen vegetation formation. Seasonal variation, in vegetation indices, is taken as indicating a more seasonal vegetation type (e.g. Lloyd, 1990; Defries and Townshend, 1994; Tucker et al., 1985; Townshend et al., 1985; Table 1.2). But do satellitederived vegetation indices really provide an accurate representation of the biological phenomenon on the ground? Contemporaneous ground data has rarely been gathered to validate spectral phenologies across large ground areas and over the annual cycle of vegetation seasonality. The association between biological and spectral changes has then been assumed rather than proved for field-based studies.

Author(s)	<b>Tropical Forest Context</b>
Achard and Blasco (1988); (1990)	$\checkmark$
Achard et al. (1988)	$\checkmark$
Arino et al. (1991)	$\checkmark$
Ashley and Rea (1975)	×
Blackburn and Milton (1995)	×
Boyd and Duane (1997)	$\checkmark$
Cross (1991)	$\checkmark$
Davenport and Nicholson (1993)	$\checkmark$
De Almeida et al. (1994)	$\checkmark$
Dethier (1974)	×
Di et al. (1994)	×
Eidenshank and Haas (1992)	×
Fischer (1994a); (1994a)	×
Gammon and Carter (1979)	×
Gregoire (1990)	✓
Gond <i>et al.</i> (1992)	$\checkmark$
Gower (1994)	×
Hame (1987)	×
Hobbs (1990)	×
Holben (1986)	×
Jones et al. (1997)	✓
Justice <i>et al.</i> (1986)	×
Justice <i>et al.</i> (1986)	✓
Justice <i>et al.</i> (1989)	×
Lambin (1996)	×
Lambin and Strahler (1994a); (1994b)	✓
Lloyd (1990)	×
Miller et al. (1990) (1991)	×
Millington et al. (1994)	×
Olson and Good (1962)	×
Prince (1986)	×
Singh (1986)	$\checkmark$
Singh and Singh (1992)	$\checkmark$
Spanner et al. (1990a); (1990b)	×
Tucker et al. (1985)	
Townshend et al. (1991)	✓
Townshend et al. (1987)	✓
Townshend and Justice (1986)	✓

Table 1.2, Examples of satellite observations of large area phenology

## **1.2.2** Satellite remote sensing: its importance in this research

Satellite remote sensing is an invaluable tool in any large-area phenological investigation. This is since it offers a high internal sampling consistency and a near-daily monitoring capability unparalleled in any other large-area monitoring technique (Jones *et al.* 1997). The satellite-sensor combinations used in this study are the ERS-2 ATSR-2 and the NOAA14-AVHRR. These systems acquire data in the visible, near-infrared and thermal wavelengths of the spectrum. Their ground resolving power is approximately 1 km<sup>2</sup> at nadir. This spatial

#### CHAPTER 1, Introduction

resolution has been demonstrated to represent the current optimal technological compromise for large-area vegetation monitoring. It results from a trade-off between the temporal, spatial, spectral and radiometric limitations of EO technology (Townshend, 1992). The same author has recommended, however, that the next generation of earth-observing systems (for such applications) also have spatial resolutions of 0.25 and 0.5 km<sup>2</sup>. It should also be noted that, although the satellite-sensor combinations, used in this study, represent the most ideal instruments for research into large-area TF ecosystem dynamics, the satellite repeat cycles and the high incidence of cloud in the humid tropics mean that useful imagery is still a precious commodity.

### **1.2.3** Ground verification: its importance in this research

Any remote sensing characterisation of TFs is problematic, since forests are architecturally complex and heterogeneous at almost all spatial scales. At the leaf scale, many different sizes, distribution patterns, shapes, colours and geometric orientations are present. At the canopy scale, trees may develop very deep canopies with foliage distributed vertically across distances in excess of 20m. Several strata may be present, and the vegetative elements may be clumped, bringing complex shading and multiple scattering effects into the response. The ground surface beneath a TF canopy may vary to include bare rock, soil, deep litter, sedges, grasses and juvenile trees. Each of these environmental and biophysical components may vary temporally and, as such, each may be characterised by a unique seasonality and set of seasonal reflectance ranges. The spectral reflectance from an area of TF represents therefore a complex integration of all these reflectance components. The task of ground verification is to determine and simultaneously monitor the most important of these factors.

Remote sensing studies (especially in logistically difficult tropical environments) typically follow a top down approach; they try to infer biological information from an image with little knowledge of the nature of the landcover. This study seeks to quantify biological change using a methodology and verification campaign designed specifically to validate a large area (1 km<sup>2</sup>) satellite image dataset. An extensive vegetation inventory and ground survey allowed a high level of confidence to be placed in the cover type attributed to the verification areas. Meteorological measurements, litterfall collections, phenological observations, hemispherical photography and overpass-synchronous radiometer readings of the vegetation then allowed

spectral phenology to be examined in parallel with observed botanical and meteorological changes.

### **1.3 RESEARCH AIM AND OBJECTIVES**

The overall aim of this investigation is to explore the associations between biological and spectral phenology. This will be achieved by monitoring biological phenology at three field sites, in three different tropical ecosystems, acquiring meteorological observations, and then comparing these data to spectral reflectance products acquired using remote sensing.

The specific objectives are as follows:

- (i) To establish a monitoring and observational protocol for determining the biological phenology and meteorological seasonality, at a large area spatial scale (i.e. one suitable for use with km<sup>2</sup> satellite data) for each of the field verification sites;
- (ii) To determine the remotely sensed spectral phenology at each of the field verification sites;
- (iii) To determine the relative importance of the environmental triggers to phenology at each of the field verification sites;
- (iv) To ascertain which, if any, of the biological phenologies at the field verification sites can accurately be characterised by a spectral phenology; and,
- (v) To investigate the relationship between spectral-spatial changes in the satellite image data and the biological phenological changes observed at the verification sites.

#### **1.4 THESIS STRUCTURE**

This thesis is presented over eight chapters. In the first, the concepts of biological and spectral phenology have been introduced and set within a TF context. The research aim and objectives have been defined, and the importance of remote sensing emphasised. The second chapter reviews TF ecosystems with reference to their spatial distribution and structure. The potential environmental triggers of phenology are examined with particular attention being paid to electromagnetic radiation, and the spectral reflectance characteristics of vegetation. The concept of forests as dynamic biotic assemblages then leads to a discussion of TF phenology. Finally, the techniques for observing phenological changes in vegetation on the ground and using satellite-based earth observation systems are reviewed. Chapters three and four detail the methodologies employed for collecting and processing the ground-based and satellite-derived datasets respectively. Details are provided of the design, construction and operation of experiments, as well as the routines used to calibrate the data collected. Chapters five and six are similarly paired and detail the analysis of the discrete datasets. Chapter five provides an analysis of the ground verification data and is divided into two sections; meteorological observations and biological phenological monitoring. Chapter six describes the remotely sensed data analysis and is also presented in two sections. First, a spectral analysis of each monitored TF verification site is presented. Secondly, an analysis of the spectral and spatial attributes of the data is attempted. Particular attention is given to view and illumination geometries as artificial cues to the satellite-observed seasonality. The seventh chapter represents a synthesis of the ground-based and remotely-derived time-series. Both qualitative and quantitative analyses are presented as the associations between spectral and biological phenologies are investigated. A detailed description of the biological processes contributing to the integrated spectral phenology for each field verification site is attempted. Finally, chapter eight attempts to focus the conclusions of the preceding sections. Each of the primary research objectives are re-evaluated and the final conclusions stated. Some recommendations for continuing research are also suggested.

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# CHAPTER 2 LITERATURE REVIEW

## 2.1 INTRODUCTION

The aim of this chapter is to review and develop the core concepts of this investigation (outlined in section 1.2). To achieve this, seven broad topics have been contrived. Each details a discrete research area (sections 2.2 to 2.8). In section 2.2, TF ecosystems are reviewed with special reference to their distribution and structure. The concept of TF ecosystems as dynamic and changing biotic assemblages is emphasised leading to a discussion of the environmental (seasonally variant) triggers to TF phenological events (section 2.3). Electromagnetic radiation is discussed (section 2.4) and the spectral reflectance characteristics of vegetation outlined (section 2.5). TF phenology is described (section 2.6) and the various techniques for observing seasonal changes in vegetation, both on the ground (section 2.7) and using satellite based earth observing systems (section 2.8), are reviewed. These discussions are progressed from the theoretical, to the experimental, by reference to the practicality of monitoring the variables described in section 1.3. Since the elegance of science lies in its interconnections, the factors linking these topics are stressed throughout.

## 2.2 TROPICAL FOREST ECOSYSTEMS

The tropical regions of the world are located between two meridians (the tropics of Cancer and Capricorn). These demarcate the zone where the sun can lie at zenith in the sky. As a consequence of their geographic location, the tropical and equatorial regions are characterised by the receipt of large amounts of solar radiation throughout the year. These illumination conditions (and the implied high temperatures), if accompanied by sufficient atmospheric and surface water, create conditions ideal for plant growth. The resultant life forms are the tropical forests (TFs).

Fossil records suggest the first TFs existed 60-130 million years ago (the Cretaceous period) reaching their greatest areal extent approximately 45 million years ago (Whitmore, 1990; Reading *et al.*, 1995). Neotropical forests today cover c. 4 million km<sup>2</sup>, representing almost half of the world's present total TF area (8.3 million km<sup>2</sup>) (Whitmore, 1990). By far the largest neotropical formation occupies the Amazon Basin, Guyanan Plateau and the western foothills of the Andes (Reading *et al.* 1995) (Figure 2.1). This vast expanse is punctuated by areas of savanna and increasingly by human clearance. Other significant areas

of TF, in Latin America, occur: (i) on the western side of the Andes along the Pacific coasts of northern Ecuador and Colombia; (ii) in contiguous Central America (and many of the Caribbean islands); and (iii) on a narrow coastal strip of south-east Brasil. Seasonal semi-deciduous forests also occur along the southern periphery of the Amazonian *hylaea* (Walsh, 1996; Figure 2.1). These drier TF types contain both Amazonian humid tropical forest species and vegetation elements from the *cerrado* and Chaco ecoregions. An ecotonal progression (characterised by an increase in the degree of deciduousness, the extent to which leaf fall is synchronous with meteorological changes, and the degree of canopy openness) is observed along this southerly vector (Walsh, 1996; see Figure 2.1). The forests of this vegetation progression form the basis of this study (Figure 2.2).

TF ecosystems are of special interest to ecologists since they contain extremely high species ( $\chi$ ) and within habitat ( $\alpha$ ) diversity (Erwin, 1988; Gentry, 1982; Gentry, 1988; Prance, 1983; Tuomisto *et al.*, 1994; Clinebell *et al.*, 1995) and their biomass is often very high (i.e. often exceeding 500 t ha<sup>-2</sup>, Pires and Prance, 1985). The wealth of experimental opportunities that such biomes present have led to a substantial research literature. TFs are complex dynamic systems. Many environmental factors influence their form, character and diversity. This section has therefore been divided into several parts in order to facilitate coherent discussion. The classification schemes used to differentiate between the many TF forms are reviewed first; special attention is drawn to the abiotic criteria used by some researchers to aid in their distinctions. TF structure, organisation and vegetation architecture are then examined along with methods for their inventory.

# 2.2.1 Tropical forest types and classification systems

So far in this thesis I have implied that there are different types of TFs. As this is the case, it is important to know what criteria can be used to distinguish TF vegetation communities from each other, and, whether knowledge of these classification schemes may aid in an understanding of phenological processes. In this section, various attempts at discriminating between and classifying TF ecosystems are reviewed. In particular, bioclimatic classification schemes are scrutinised in order to glean any information about the abiotic factors relevant to TF phenology.

#### CHAPTER 2, Literature Review

There have been many approaches to the description and classification of vegetation. Kuchler (1967) and Shimwell (1971) divide those based on vegetation floristic or physiognomic characteristics (e.g. Veloso et al., 1991) from those that incorporate information relating to climatic or seasonality variables (e.g. Leith, 1974; Norwine and Greegor, 1983. Richards, 1939; Beard, 1955; Longman and Jeník, 1987 or even Von Humboldt, 1805 in his map of the vegetation of Ecuador). Holdridge (1967) developed a vegetation-climate association, presenting a bioclimatic scheme for the classification of vegetation. In this system, tropical regions were defined as those having a biotemperature exceeding 24°C. In all, seven Life Zones were proposed (Lowland, Premontane, Lower montane, Montane, Subalpine, Alpine and Nival), each defined according to its biotemperature, mean annual precipitation, altitude and evapotranspiration (Figure 2.3). This classification scheme is important since it represents the first empirical attempt at directly correlating tropical vegetation communities to climatic parameters. Although a useful starting point, the scheme is perhaps too dominated by altitudinal sub-divisions to accurately identify differences in TF type that are a function of environmental variables other than precipitation and temperature, both of which show steep altitudinal variation in the tropics. Additional problems include the use of climatic means (within altitudinal zones) rather than annual ranges or other climatic indices. This classification scheme does however illustrate clearly the principal role played by water in defining tropical vegetation type and probably also therefore in TF phenology.

Whitmore (1990) proposed a classification scheme for the forests of the tropics. This was based on the concept of perhumidity (the degree of continuity of wetness in a tropical climate), soil type and location (predominantly elevation). This scheme identified twelve evergreen TF (rainforest) types within four main classes.

- (i) The dryland forest types of lowland evergreen, limestone and ultrabasic areas.
- (ii) The montane forest types of lower, upper and subalpine forests.
- (iii) The freshwater wetland forest types of permanent, seasonal and peat swamp forests.
- (iv) The coastal forest types of mangrove, brackish water swamp forests.

Evergreen TF classes were defined as occurring in climatic regions where every month received at least 100 mm of rainfall (on average). This classification of tropical vegetation, is note worthy because of its distinction between dryland and wetland forests. The emphasis on the role of soils is also interesting since from a phenological perspective the water storage potential of a soil is probably also an important factor.

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Walsh (1996) attempted an allocation of vegetation classes corresponding to climatic variables, based on the work of Whitmore (1990), extending the concept of perhumidity. TFs were defined as evergreen when occurring in areas with 0-3 months of rainfall under 100 mm (i.e. occurring in what Walsh defines as a tropical superwet or wet climate, Figure 2.1). Tropical evergreen seasonal forests were defined as occurring where 3-5 months have rainfall under 100 mm (i.e. a tropical wet seasonal climate). Semi-evergreen, seasonal TFs and deciduous seasonal TFs occur in areas where 5 or more months receive under 100 mm of rainfall (i.e. tropical wet-dry climates) (Prance, 1983). This classification attempts to build more flexibility into Whitmore's (1990) rather restrictive definitions, by giving additional weight to long dry periods and very wet epochs (Walsh, 1996). It is note worthy that, water again is the principal 'limiting' classification parameter but more significantly, the use of integrated climatic variables (i.e. periods of extended rainfall or dryness) allows the association between TF vegetation and the seasonality of a climatic variable to be examined. It follows then that a TF formation may be a composite response to a number of inter-related, coupled and integrated abiotic factors. It is also likely that TF phenological processes are driven by similar integrations of climatic variables.

Pires and Prance (1985) produce a hierarchical classification of the principal vegetation types of the Brasilian Amazon, again distinguishing the dryland forest formations (*terra firme*, those not reached by periodic inundation) from the wetland formations. The latter are further subdivided into two main types: *varzéa* (areas annually flooded by muddy or white waters) and *igapo* (areas annually flooded by black or clear waters) (Black *et al.*, 1950). Other more physiognomically-based Amazonian vegetation classification systems have also been attempted (e.g. that of Veloso *et al.*, 1991; see Appendix 2.1).

In conclusion, the task of classifying such a heterogeneous biome is a difficult one. Each researcher (and their research discipline and paradigm) may have a distinct approach to the orderly arrangement of the vegetation mosaic. The Life Zone System of Holdridge (1967) and that of Veloso *et al.* (1990) represent well the dichotomy of TF vegetation classification schemes. Holdridge's life zones relate vegetation to climate almost without reference to vegetative parameters, whilst the classification of Veloso *et al.* uses terms such as 'seasonality' without definition. The principal elements used to distinguish the distribution of TFs are often meteorologically based, the amount and temporal distribution of available water (rainfall, humidity and aquifer) largely defining the different tropical climatic zones, and therefore the

TF vegetation formations. These parameters will also be important in the study of TF phenology.

## 2.2.2 Tropical forest structures

As viewed from above (Plate 2.1), a TF appears a near continuous heterogeneous surface. This effect is produced by the countless interlocking crowns of the canopy trees (which are typically 30-40 m in height). Emergents (larger protruding individuals, up to 50-60 m tall)



Plate 2.1 TF Mosaic (Viewed from the Air) (Parque Nacional Noel Kempff Mercardo, Courtesy of Dr. Jane Wellens)

punctuate this surface, whilst gaps of varying dimensions lie in shade. This canopy surface has two major modifying effects on the microclimate below the canopy. Firstly, it provides protection from heavy rainfall (precipitation being filtered so that much of the water reaches the ground as a fine mist). Secondly, and more importantly, it modulates the incoming solar irradiance, changing both its intensity and spectral composition. Beneath the canopy smaller trees and shrubs are found, each adapted to the

specific microclimate they occupy within the vertical and horizontal mosaic. The lowest levels of the TFs are often in deep shade, only c. 2 per cent of the irradiance incident upon the canopy penetrating to the forest floor (Lee, 1987; Tasker and Smith, 1977). Here there is little air movement and a higher relative humidity. A few specialist plant groups have evolved to exploit these conditions (e.g. saprophytes, which obtain nutrients from decaying plant matter) but most vegetation scavenges for the scarce environmental resource of light.

TFs are then complex and dynamic spatial structures. The intricate architecture of the vast number of plant species they contain creating an environment that varies not only spatially but also temporally (Reading *et al.*, 1995). It may be argued however that within these spatial-temporal complexities there are factors that favour convergent evolution. The pressure to survive within a particular environment determining the structural form (architectural arrangements) of the dominant vegetation (Mori and Boom, 1987). For instance, the trees of

### CHAPTER 2, Literature Review

the canopy all have a similar form, indeed they all look remarkably similar (i.e. they all are tall, have long thin boles and flattened canopies). In contrast, sub-canopy trees and those of the understorey are shorter with larger ovoid (vertically elongated) crowns. Furthermore, at the leaf scale, the differentiation of leaves belonging to different species (within the same layer) on the basis of size or pigmentation is difficult. Arguably, this similarity of form extends to a similarity of function, at least in the context of photosynthesis and transpiration.



Since the light environment is the primary constraint on energy partition and processing (photosynthesis), a vertical zonation or stratification is a logical firstorder simplification of the vegetation structure.

**Plate 2.2 TF Spatial Structures** 

## 2.2.2.1 TF vegetation architecture and vertical stratification

TF vegetation has often been described as vertically stratified (e.g. Bear, 1955; Webb and Tracey, 1967; Webb *et al.*, 1969) see Table 2.1. The concept is however often loosely applied: being used to describe: (i) vertical stratification of leaf mass; (ii) vertical stratification of individuals; and (iii) vertical stratification of species (Grubb *et al.*, 1963; Grubb and Whitmore, 1966a; Grubb and Whitmore, 1966b; Smith, 1973). In the context of this study it is the vertical stratification of the leaf mass that is most important.

	Layer	Height	Main floral elements
40m-	A Upper Tree	>25m	Emergents, Woody Climbers and Epiphytes
30m-	<b>B</b> Middle Tree	10-25m	Large Trees and Woody Climbers
20m-	C Lower Tree	5-10m	Small Trees and Saplings
	D Shrub	1-5m	Seedlings, Shrubs
	E Herb	<1 m	Seedlings, Grasses, Ferns and Bryophytes
	Table	2.1 Vertica	I Stratification of TFs,

Richards (1939) first introduced the concept of leaf stratification to tropical ecology, suggesting TFs had two *photic* zones. These highly different environments for biotic existence were defined as the *euphotic* layer (or canopy stratum) which intercepts sunlight directly and the *oligophotic* layer (or understorey stratum) which intercepts sunflecks, scattered and transmitted radiation. Longman and Jeník (1987) and Klinge *et al.* (1975), amongst others, expanded this TF stratification concept to describe three, or more vertical layers (see Table 2.1). Klinge *et al.* (1975) demonstrated that 85% of total phytomass (and nearly 50% of leaf phytomass) occurred in the A and B strata (see Table 2.2 and Table 2.3) and commented on the different leaf physiological adaptations present. Other researchers (e.g. Cain *et al.*, 1956 and Grubb *et al.*, 1963) report problems in the identification of strata however, and some authors (e.g. Frankie *et al.*, 1974) have even discredited the notion of distinct layers in TFs altogether. Francis Hallé (1978) comments that although tree architecture may vary greatly within a stratum (due to physiological constraints), from the perspective of energy capture, such a delineation has merit (Tomlinson, 1978; Hallé *et al.*, 1978).

Without doubt, the impact of differing light environments on leaf physiology is profound. This topic is discussed in detail in section 2.5. However, this photic division may also be extended to other meteorological parameters (e.g. temperature, humidity, wind speed etc.). These are discussed in section 2.3.2.

Stratum	Dicotyledonous Trees (number / Ha)	Palms (number / Ha)	Leaves (Metric Tonnes / Ha)	Branches & Twigs (Metric Tonnes / Ha)	<b>Stems</b> (Metric Tonnes / Ha)	Total Weight (Metric Tonnes / Ha)	Percentage Weight
Α	50	0	2.3	48.7	139.2	190.2	27.6
В	315	0	7.1	123.1	269.3	399.5	58
<b>C</b> <sub>1</sub>	760	15	3.9	26.1	47.3	77.3	11.2
C <sub>2</sub>	2,765	155	2.0	3.6	10	15.6	2.3
D	5,265	805	2.2	0.7	1.8	4.7	0.7
E	83,650	-	0.6	0.2	0.6	1.4	0.2
Total	93,780	-	18.1	202.4	468.2	688.7	100
%	$G_{T_{1}}^{i}$ ( $\hat{T}_{T_{2}}^{i}$	an tang ang tanggang	2.6	29.4	68	100	

Table 2.2 Typical composition of a TF vertical section,<br/>after Klinge et al. (1975).

Klinge *et al.* (1975) divide their tropical forest in two six stratum, dividing the C stratum into C1 and C2 on the basis of observed structural differences.

T	able 2.3, The vertical organisation of aerial
	phytomass in a Central Amazonian TF,
	after Klinge et al. (1975)

in desire, tribu alah, ang in desire, Ditot tributan tributan terterangan alahar j	Metric Tonnes (Ha)	Percentage of Total
Leaf Matter	Cosson (19	ano unti
Dicotyledonous Trees > 1.5m height	14.1	1.9
Palms > 1.5m height	0.34	0.5
Vegetation < 1.5m height	0.6	0.1
<b>Branches and Twigs</b>		
Dicotyledonous Trees > 1.5m height	202.2	27.5
Vegetation < 1.5m height	0.2	0.03
Boles	all and the	
Dicotyledonous Trees > 1.5m height	465.5	63.3
Palms > 1.5m height	2.1	0.3
Vegetation < 1.5m height	0.6	0.1
Other Plants		
Lianas	46	6.3
Epiphytes	0.1	-
Total Aerial Phytomass	743.9	100%
Total Root Phytomass	255	
Total Phytomass	989	
Standing Dead Wasd	76	27
Litter Dead Wood	18.2	6.5
Fine Litter (Total)	72	2.5
Leaf	4	2.5
Wood	3	
Fruits & flowers	0.2 .	



Plate 2.3 TF Vertical Stratification

# 2.2.2.2 Tropical forest inventory

Measuring and recording the structural complexities of a TF is an immense challenge. It has often been attempted however, the literature on quantitative ecological inventory of South American TFs being considerable. Comparison of these data is difficult however since the survey methods employed are diverse (Campbell *et al.*, 1986; Hommel, 1990). Inventory plot sizes range from 0.10 hectare (Gentry, 1982) to 3.55 hectares (Pires *et al.*, 1953) and the ideal plot size is the subject of debate (for a comprehensive review see Hommel, 1990). In addition, studies also are often limited to specific minimum tree girth classes. Minimum diameter at breast height (dbh) ranging from 2.54cms (Gentry, 1982) to 30 cms (in the case of Heinsdjik and de Bastos, 1965). Hommel (1990) concludes that reasonably small plot sizes (0.1 ha) of all terrestrial vegetation (regardless of age, dbh, class, growth form or size) should be sampled in preference to other plot sizes. Commonly monitored TF inventory parameters include:

- (i) <u>Height</u>. Two expressions are useful. The total height of the tree (the vertical distance from the base of the tree to its upper most point), and/or height from the base of the tree to its lowest branch. The difference between the two yields the optical depth of the canopy. Various methods can be used to obtain these parameters, from direct measurement (climbing or using tethered balloons, Prance *et al.*, 1976) to visual estimations (Heinsdjik and de Bastos 1965). More commonly a clinometer is used with standard trigonometrical principals (see Appendix 2.2 and Philip, 1983).
- (ii) <u>Bole dimensions</u>. Diameter at breast height (dbh) is usually measured at 1.3 metres above the soil level (litter and tree debris having been removed) (Philip, 1983). On trees forking below 1.3 metres each stem is measured and recorded separately. Where buttresses are present measurements are taken as the above buttress height. To obtain these measurements the standardised system of the IUFRO recommends an over bark measurement using Loggers' callipers (or tapes).
- (iii) <u>Crown dimensions</u> (the horizontal extent of the canopy). Measurement is undertaken at the cardinal compass points outwards from the base of the tree to the point on the ground where a vertical projection of the crown edge falls. Qualitative descriptions of the vertical shape are also useful, e.g. geometrical generalisations: ovoid, sphere, ellipse, being the most commonly described (Hallé, 1978).
- (iv) <u>Crown depth</u>. See tree height.
- (v) <u>Species</u>. Recording the vegetation species using both common (local) and scientific names, approximate age and other details such as the amount of liana infestation are good practice in tropical forestry. Complications may arise when species have several local names, or a local name is applied to more than one species. Names may also be age dependent.

Data on botanical phenology are rarely collected.

# 2.3 ABIOTIC FACTORS IN TROPICAL FOREST PHENOLOGY

Leith (1974, pp. 4) defines plant phenology as 'the timing of recurring biological events.' but notes that an understanding of the processes involved may only be obtained by reference to 'The causes of their timing with regard to biotic and abiotic forces...'. In this section, the potential abiotic cues to phenological processes in tropical ecosystems are identified.

## 2.3.1 General meteorological effects

At a continental scale, the equatorial limb of the Hadley cell dominates the weather and climate of the humid neotropics. In Amazonia, this general circulation is modified by the Andean cordillera which forms a large and effective terrestrial barrier within the troposphere. These mountains cause air masses to become particularly unstable and buoyant and practically exclude the affects of the Pacific air masses from Amazonia (Reading *et al.*, 1995). Two major air masses do affect the Amazonian region however, the equatorial continental and equatorial maritime systems (Figure 2.4). The conventional zonal circulation explanation is that during the austral summer (January), the inter-tropical convergence zone (ITCZ) bulges southward over Amazonia causing the equatorial continental air masses to dominate the region. This leads to rainfall and hot humid conditions. By the austral winter (July) the maritime air masses have migrated northwards behind the ITCZ allowing equatorial maritime air-mass domination of the area (Vaun-Williams, 1982). This results in a cooler, drier season.

Given this seasonality of meteorological conditions in Amazonia, what then are the potential abiotic cues to TF phenology in this region? Although day-length is more or less static at these latitudes (cf. Appendix 2.3) the seasonal north-south migrations of the ITCZ and associated convective rainfall belts will cause changes in: sunlight intensity and spectral composition, temperature, cloudiness, humidity, water availability (encompassing precipitation, evapotranspiration, humidity and soil parameters), windspeed and barometric pressure. The diurnal ranges of these parameters may also be important since often these are greater than any seasonal variations. The seasonal and diurnal variation of these parameters are summarised in Table 2.4.

Meteorological Variable	Seasonal Variation	Potential as a Phenological Trigger	Diurnal Variation
Sunlight Intensity and Spectral Composition	Primarily controlled by cloud cover (see section 2.4)	Minimal, although significant seasonal variations are expected between strata (see section 2.4)	Great
Air Temperature	Seasonal variations in air temperature are minimal and are largely a function of the seasonality of cloud cover and humidity conditions (Longman and Jenik, 1987).	<b>Minimal</b> , although commonly cited as an abiotic control on phenology. For the purposes of comparison to a botanical dataset accumulated temperatures are often used (Synder, 1985). The most common of these is the degree-day (heat unit). Here mean daily temperature is summed and divided by the number of integrated days. For examples of the calculation of the degree-days see Appendix 2.4.	Air temperature has a distinct diurnal rhythm linked to that of humidity. This results in an amelioration of diurnal variations in the wetter austral summer.
Water Availability	Seasonal variations in precipitation are variable (ranging from minimal to pronounced).	<b>Potentially great,</b> periods of water surplus (when rainfall > potential evaporation, PE) and water deficit (when PE > rainfall) are important potential phenological controls.	Relative humidity and PE have distinct diurnal rhythms linked to those of temperature.
Cloudiness	Clouds are common in the tropics (especially where the ITCZ is most active). The austral summer (wetter) season generally being more overcast (daily average 6 octas) than the austral winter (drier) season averages 4 octas (Longman and Jeník, 1987).	Modifies Sunlight Intensity and Spectral Composition	A Cumulo-Nimbus (convective) build up of clouds is common throughout the year after midday. This poses serious problems for the acquisition of remote sensing imagery in the afternoon.
Wind-speed	See Micrometeorological effects (section 2.3.2)	Minimal	Poorly Known

Table 2.4 Meteorological factors potentially affecting TF phenology

# 2.3.2 Micro meteorological effects

The microclimate of a TF may be defined as that area of the atmosphere to which the living organisms are directly exposed. Within this portion of the (near) atmosphere, individual plant elements act to create small scale but important differences in climate (Elston and Monteith, 1975). In this way TF architecture affects air temperature, soil temperature, air vapour pressure, leaf temperature, soil heat exchange, wind speed, and precipitation interception (Ross, 1981; Norman and Campbell, 1989; Nobel, 1991; Nobel *et al.*, 1993). When searching for potential abiotic triggers to phenological events the microclimate may be more relevant than the general meteorological condition. The nature of the TF interaction with these variables is complex, but may be stratified vertically in a manner described in 2.2.2.1.

Strata	Microclimate			
Canopy / Clearing (euphotic stratum)	Seasonally the more variable than the oligophotic stratum. Generally, it has a lower relative humidity, higher daytime temperatures and higher evaporation rates than the oligophotic stratum (Odum <i>et al.</i> , 1963). In fact, evaporation rates found in the forest canopy are similar to those found in savanna environments. A pronounced diurnal temperature-humidity regime is found and wind speed is a significant variable since it effects evapotranspirational rates. The main limiting phenological factor is probably WATER			
Understorey / Ground (oligophotic stratum)	Less seasonally variant than the euphotic stratum, with a higher relative humidity and lower year-round evaporation rates (Longman and Jeník, 1987). Diurnal temperature-humidity variations are moderate. <b>The main limiting phenological factor is probably LIGHT</b>			

 Table 2.5 Microclimate of tropical forests, after Richards (1939)

## 2.3.3 Tropical Forest Soils and Geomorphology

Descending the eastern face of the Andean cordillera towards the Amazon basin a succession of planation beds are encountered. Palaeozoic, Cretaceous and the widespread Tertiary and Quaternary formations of the Brasilian Shield dominate (Grubb *et al.*, 1962; Eden, 1990). A major distinction exists between the poorly drained areas of the Amazon floodplain (and its major tributaries along the Andean border) and the elevated *terra firme* which comprise c. 90% of the Amazon basin. These different soil formations, that have evolved in different lithologies and hydrological conditions, will have very different characteristics (with regard to water retention and storage). Such differences are important in determining the phenological stratagem of vegetation.

Soils that originate from the Andean uplift are mainly Fluvisols and Cambisols (FAO/UNESCO classification) and occur on recently formed alluvial sediments of floodplains where sedimentation is no longer active and pedogenic horizons have developed. Such soils are characterised by year round-water availability, are moderately developed and may be seasonally inundated. When these soils are flooded, water enters the soil and the air pores are compressed. At first, this leads to increased percolation through the soil, but eventually the pores become clogged with microbial waste and disaggregated soil particles. This decrease in percolation may result in flooding and inundation. Such conditions lead almost instantaneously to changes in the chemical equilibrium of the soil, oxygen levels plummet, and the micro-organism balance experiences a huge increase in anaerobes. Soil equilibrium may then change from an oxidised to a reduced state very quickly causing increases in soluble ammonium, phosphorus, manganese and ferrous iron levels (Pires and

Prance, 1985). These changes in soil properties will affect leaf physiological processes and may be manifest in canopy phenology.

Soils of the shield region are based on ancient rocks. They are well weathered, have a low natural fertility and are derived from rocks comparatively poor in nutrients. They are characterised by neutral to moderately acid pH values, but within TF formations bases supplied by the plant litter prevent acid conditions from developing (Bridges, 1978). In savanna areas, soils are characterised by a thin humus layer, lateritic horizons and sandy textures (Ringrose *et al.*, 1989). Common soil types include Lixisols which grade to Ferralsols where precipitation rises. These soils are friable in spite of their high clay content, and easily penetrated to great depth by water and roots. The dominant downward movement of water leads to excessive base leaching, often forming a lateritic horizon. This may be up to 10m thick and where present effectively limits root growth and drainage. Vegetation must then rely on rainwater-born elements and the extremely rapid recycling of organic materials. Such soils are often described as 'droughty', and the phenological responses on these soils mainly relate to soil water availability.

## 2.3.4 Miscellaneous factors

Local topographic factors may play a major role in the interaction of the atmosphere with the land-surface. Aspect and slope can affect the receipt of shortwave irradiance, soil and vegetation temperatures, the pattern of wind-flow, the degree of shelter, and the amount of precipitation received (Jones, 1992). Topography may also affect the water balance, due to surface runoff creating 'water shedding' and 'water receiving' sites over a variety of spatial scales.

# 2.4 ELECTROMAGNETIC RADIATION

Electromagnetic radiation (EMR) is the most dynamic of the abiotic factors affecting TF phenology (Evans, 1966). It is also the medium of detection used by the satellite remote sensing systems used in this study. EMR interacts with particles in a complex manner, i.e. by changing their electronic, vibrational and rotational properties. As such, it exhibits the behaviour of both waves and particles. Within the waveform paradigm, EMR has associated electric and magnetic fields. These are orthogonal to each other and to the direction of propagation (Figure 2.5). These fields oscillate periodically and so may be described by sine

waves. Their frequency (or wavelength) is a function of the energy of their associated quanta. Planck described this relationship as:

$$E = vh = ch/\lambda$$

(Planck's law)

or:

$$M_{\lambda} = \frac{2\pi hc^2}{\lambda^5 (e^{hc} / \lambda kt^{-1})}$$
[2.2]

Where: *E* is energy; *v* is frequency; *h* is Planck's constant (6.62 x 10<sup>-34</sup> Js); *c* the velocity (of EMR in a vacuum).  $M_{\lambda}$  the spectral radiant exitence; k is Boltzman's constant; T is temperature (Kelvin units).

An integration of Eq. 2.2 (over the whole spectrum) yields the total radiant exitance (M). Following Stefan-Boltzmann's Law, this is proportional to the fourth power of the absolute temperature of the object (solar source):

$$\mathbf{M} = \mathbf{\varepsilon} \boldsymbol{\sigma} \, \mathbf{T}^4 \tag{2.3}$$

where  $\varepsilon$  is the emissivity (< 1),  $\sigma$  is the Stefan Boltzmann constant (5.6 \* 10<sup>-8</sup> W <sup>-2</sup> K <sup>-4</sup>) and T is temperature in K (Kelvin units).

Differentiating M and solving the maximum (according to Wien's displacement law) the wavelength ( $\mu$ m) at which the maximum amount of radiation is emitted ( $\lambda_{max}$ ) decreases as the temperature of the body increases:

$$\lambda_{\rm max} = 2897/{\rm T}$$
 [2.4]

where: T is the surface temperature in Kelvin (K).

This equation assumes the energy distribution for emissions emanate from a true black body ( $\epsilon = 1$ , at all wavelengths). For a detailed review see Lillesand and Kiefler (1994).

Solving Eq. 2.4 for the sun, a peak emission 0.48  $\mu$ m is obtained. Within this study, EMR centred on this wavelength (from 0.4 to 2  $\mu$ m) is utilised. The interaction of tropical vegetation with these wavelengths of EMR, from emission (from the solar source) to detection (by the satellite sensor) is summarised in Figure 2.6. Here V represents the viewing conditions of the sensor, including:

(i) the satellite's attitude and movement; and

[2.1]

(ii) the dynamics of the scanning mechanism (the sensor IFOV, the spectral characteristics of the EMR wavebands, and the transfer function of the sensor optics).

I defines the illumination conditions. These may vary as a function of the magnitude, and spectral composition, of atmospheric irradiance, and as a function of the earth's orbit around the sun. These are relatively stable in the tropics, although, solar events such as sunspots and flares may cause random variations.

A are the atmospheric conditions. The atmosphere may scatter and/or absorb solar irradiance as it passes through it. This may result in direct solar radiation (a beam of parallel rays reaching the TF from the solar disk that has passed through the atmosphere of the earth almost unattenuated) or diffuse solar radiation (that scattered in the atmosphere). The later reaches the TF from all directions of the sky simultaneously.

C represents the canopy characteristics. These are defined by the structure and radiometric characteristics of the TF vegetation.

S the substrate. This may be defined as a composite of surface characteristics, topographic characteristics (surface roughness) as well as composition (structure, physical and chemical characteristics) of the underlying soil or rock.

Both V and I are both relatively stable and predictable (from orbital parameters, design characteristics, and calibrations of the sensor). A, C and S are all unknown, and are temporally and spatially variable. C and S (canopy and soil characteristics) are the parameters of most interest in this research. They are, however, integrated spatially as a function of a large number of factors, including the spatial sampling scale (the instantaneous field of view, IFOV) and the vegetation spatial mosaic. A however is an unwanted source of random fluctuation (or noise) the nature of its effect on a remotely sensed signal must therefore be quantified.

# 2.4.1 Atmospheric attenuation

The atmosphere acts to attenuate all EMR incident on terrestrial objects. Such atmospheric perturbations affect the direction, intensity and spectral composition of incident EMR (Barett and Curtis, 1992). These effects result from the scattering and absorption of EMR within the atmosphere principally due to the effects of gas molecules, aerosol particles, dust and water vapour. The nature and magnitude of these modulations varying as a function of the following.

- (i) The path-length of the radiant flux through the atmosphere. This will vary both diurnally and seasonally (although seasonal variation will be minimal in the tropics).
- (ii) Atmospheric optical density. This is affected by the tropospheric weather systems, water vapour, dust and smoke aerosols.
- (iii) The position of the sun relative to the Earth's surface. Since the orbit of the Earth around the sun is an ellipse, the earth-sun distance is not constant. As a consequence, the EMR reaching the top of the atmosphere varies from its mean value by +/- 3.3% p.a. (with a minimum in July and a maximum in January, Collinbourne, 1966).
- (iv) Wavelength. The process of atmospheric scattering decreases inversely with wavelength, resulting in the severe attenuation of shorter wavelengths of EMR (i.e. visible light). The three most common attenuating processes have been termed Rayleigh, Mie and non-selective scattering. Rayleigh scattering occurs when an object smaller than the wavelength of EMR modulates the flux, e.g. gas molecules. The resulting attenuation is inversely proportional to the fourth power of the wavelength and directly proportional to the density of the scattering medium. Shorter wavelengths are therefore principally affected. Mie scattering is the result of particles that are of comparable (or greater size) to the wavelength of the EMR (usually water vapour and aerosols). Longer wavelengths are therefore most affected. Non-selective scattering is caused by water droplets suspended soil particles, smoke nuclei etc., that are of a much greater size than the wavelength of the incident EMR. The subsequent scattering is independent of wavelength.

On reaching the Earth's surface, solar radiation may be divided into two components based on whether the irradiance has been scattered (by the atmosphere), diffuse radiation, or has passed through the atmosphere without interference, direct irradiance. The ratio of diffuse to direct radiation varies with sun angle, cloud cover and type. These different interaction histories produce distinct spectral qualities in scattered and direct light (Tooming and Niilisk, 1967; Perelyot, 1970). These are summarised on Table 2.6. The relative proportions of direct and diffuse radiation are relatively stable in the tropics since seasonal changes in the solar path length are minimal. However, seasonal changes in atmospheric optical depth may change this ratio. For example, in the drier austral winter, savanna fires and dry soil conditions may result in increased atmospheric aerosols and scattering, and a more diffuse radiation flux.

Waveband (µm)	<b>PAR %</b> (0.4 - 0.7)	<b>NIR %</b> (0.7 - 2.0)
<b>Direct Radiation</b>	42	56
<b>Diffuse Radiation</b>	65	25
Total Radiation (on a cloudless day)	50	47

Table 2.6 Percentage of PAR and NIR in the spectrum of direct, diffuse and total solar radiation, adapted from Ross (1975); Tooming and Niilisk (1967); Perelyot, (1970)

# 2.4.2 Significance of EMR for plant growth

Ross (1975) and Jones (1992) both divide the interaction between EMR and plants into three distinct categories (thermal, photosynthetic and photomorphogenetic) (Table 2.7).

The thermal effects of radiation are important since more than 70% of EMR absorbed by plants is converted into heat and used as energy for transpiration and convective heat exchange with the surrounding air. These exchanges determine the temperature of leaves and of other plant parts, and hence influence the rate of processes such as photosynthesis and transpiration. In the humid tropics, thermal conditions are usually optimal for plant prosperity.

The photosynthetic effects of EMR. A portion of solar radiation PAR (Photosynthetically Active Radiation, 0.4-0.7  $\mu$ m), which may be up to 28% in terms of total energy, may be used in photosynthesis and stored chemically in high-energy organic compounds (Rabinowitch, 1951).

The photomorphogenetic effects of EMR. The spectral quality and energy content of EMR are often quoted as regulating and controlling the processes of botanical growth, phenology and development in temperate latitudes. However, at a general level in the tropics, seasonal changes in the quantity and spectral composition of EMR are minimal (cf. section 2.4.1). The affect on plant phenology is therefore also likely to be minimal. However, photomorphogenetic processes may be significant within the tropical forest oligophotic photic strata. Since here changes in the quantity and spectral processes of the canopy stratum above.

Table 2.7 Radiation waveballds and then significance for plant me, after Ross (1975)					
EMR Wavelength	(µm)	% of Irradiance	Photosynthetically Significant	Photomorphogenetically Significant	
Ultraviolet (UV)	0.29-0.4	0-4	Insignificant	Moderate	
Photosynthetically Active Radiation (PAR)	0.4-0.7	21-46	Significant	Significant	
Near Infrared (NIR)	0.7-4.0	50-79	Insignificant	Significant	
Long-wave (TIR)	3.0-100	_	Insignificant	Insignificant	

Table 2.7 Radiation wavebands and their significance for plant life, after Ross (1975)

# 2.5 THE SPECTRAL REFLECTANCE CHARACTERISTICS OF TROPICAL FORESTS

The aim of this section is to explore the interactions between tropical forests and electromagnetic energy; this is achieved in four parts. Leaf scale reflectance processes are reviewed first (section 2.5.1), leading to a discussion of TF strata spectral reflectance (section 2.5.2) and the reflectance from TF gaps (section 2.5.3). Integrated reflectance, of the many landscape components that make up a forested area, is the subject of section 2.5.4. Lastly, changes in vegetative reflectance are scrutinised (section 2.5.5).

EMR incident upon a vegetated landscape may be transmitted ( $\tau$ ), absorbed ( $\alpha$ ) and / or reflected ( $\rho$ ) (see Figure 2.7). EMR is most strongly reflected by structures of approximately the same size as its wavelength. Biochemical compounds (e.g. cell pigments) therefore dominate reflectance at the shorter visible wavelengths (0.4-0.7 µm), whilst organelles and cells dictate reflectance at the longer NIR wavelengths (0.7-1.8 µm). The modulated components of EMR can be summarised as transmission, absorption and reflectance coefficients ( $\tau$ ,  $\alpha$  and  $\rho$ ), each representing that part of the incident radiation scattered (or absorbed) in all directions of the hemisphere (Ross, 1975). The coefficients are related so that:

$$\mathbf{1} = \mathbf{\tau} + \mathbf{\alpha} + \mathbf{\rho}$$
<sup>[2.5]</sup>

This relationship is described diagrammatically in Figure 2.7.

# 2.5.1 Leaf scale interactions

The spectral reflectance of an individual leaf will vary as a function of three parameters:

- (i) leaf pigment (type and concentration);
- (ii) leaf surface features; and
- (iii) leaf cell(s) (arrangement, physiological structure and water content).

The relative contribution of each of these factors is wavelength dependent.

Generalised leaf spectral reflectance and transmittance curves are similar to those already described for green vegetation (Figure 2.7). Individual leaf signatures are thus characterised by low reflectance in the visible and MIR wavelengths (dominated by pigment and water dependent absorption features) and high reflectance in the NIR (dominated by cell structural

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features). Since the primary purpose of a leaf is photosynthesis, its first functional requirement is that PAR is able to penetrate its surface. This is possible, since the top layer of leaf cells (the epidermis) is opaque and acts as a diffuse filter to PAR (Knipling, 1970) (Figure 2.8).

Inside the leaf, pigmentation is responsible for the majority of PAR absorption.  $\alpha$  and  $\beta$  chlorophyll, xanthophyll, the anthocyanins and the carotenoids are the main photosynthetic pigments (Figure 2.9). Their relative concentrations are dependent on plant-species, leaf-age, phenological stage and leaf-health, as well as site specific factors such as shading (Lloyd, 1989a; 1989b; 1989c; 1989d).

Leaf surface features such as hairs, spines, veins and cuticular wax all have an effect on leaf reflectance (Brakke *et al.*, 1989). Since these features vary from species to species, generalised effects are difficult to quantify. Canopy stratum leaves do however tend to possess more epidermal waxes than the leaves of the understorey vegetation. Their reflectance is therefore expected to be more specular.

There is little or no EMR absorption by leaf pigments in the near infrared (NIR) wavelengths: Knipling (1970) and Gausman (1977) both estimate NIR leaf absorption at 5% (Figure 2.7). Belward and Lambin (1992) offer an explanation for this low absorption, stating that the energy levels of NIR are too low to drive the photochemical reactions of photosynthesis. The result is a region of high NIR reflectance (0.75-1.3 um) that has been termed the NIR plateau. These reflectance and transmission events result from interactions:

- (i) with the refractive index discontinuities along cell membrane interfaces, in the upper half of the leaf; and
- (ii) intercellular air spaces and hydrated cellulose cell walls of the spongy mesophyll, in the lower half of the leaf (Gausman, 1974; Lloyd, 1989a; 1989b; 1989c; 1989d) (Figure 2.8).

The rates of transmittance and reflectance are approximately equal since the scattering processes, within the leaf, randomise the directions of radiation movement (Colwell, 1974). Other cell organelles cited as relevant to this process include the lysosomes, chloroplasts, stomata, nuclei, crystals, and cytoplasm. The intensity of the NIR plateau in the spectral reflectance curve of a leaf will therefore increase as a function of the number, size, orientation and thickness of the spongy mesophyll cells (Gausman, 1977).

In the middle infrared wavelengths, reflectance is dominated by water absorption features. Liquid water possesses four absorption peaks, at 970, 1190, 1450 and 1940 nm. Leaf reflectance in the middle infrared wavelengths is therefore inversely related to total *in vivo* leaf water content (Gates, 1962; Gates and Tantraporn, 1952; Belward and Lambin, 1990; Belward and Lambin, 1992). Leaf surface water will increase the magnitude of these absorption features.

# 2.5.2 Reflectance from tropical forest strata

At a canopy scale, the interaction between EMR and tropical vegetation is more complex than at the leaf scale. Not only do the leaf reflection processes, outlined above, need to be considered, but simultaneously the spatial distribution, density and orientation geometry (both with regard to the solar source and the viewer) of the leaves need to be accounted for. Warren-Wilson (1965) modelled these interactions using three parameters: the foliage area per unit area of ground (commonly termed LAI), the foliage area orientation (commonly termed LAD), and the dispersion foliage area.

Hall (1990) demonstrated that the effect of varying LAI (leaf area index) was profound (Figure 2.10). At high LAI values, the spectral response of a canopy approximates that of a single leaf (Figure 2.9). Whilst at a low LAI, substrate reflectance (in this case soil) becomes an important modulating factor to the reflectance signal. Goel (1988) noted that LAI reaches an asymptotic reflectance (at 2-3 in the visible wavelengths; and 6-8 in the NIR). This observation implies that changes, in leaf area, above these asymptotes will not alter their reflectance characteristics further. Such changes will be therefore undetectable using any spectral reflectance methods (e.g. remote sensing and radiometry).

Leaf Angle Distribution (LAD) is species dependent and has a strong vertical and seasonal dimension (Ross and Nilson, 1967; Ross and Ross, 1969). The angle at which the foliage is inclined to the horizontal (azimuth orientation) is usually ignored whilst the angle of inclination to the zenith (vertical) is often used in botanical plant descriptions. LADs are important since they determine the proportion of the leaf surface (and therefore substrate and shadow) presented to both the observer and sun.

The dispersion of the foliage area may be expressed as percentage cover (the proportion of the plant components visible at nadir), a clumping factor, or by noting the vertical distribution of foliage elements, e.g. the foliage area density function a(z). This determines the foliage area in a unit space volume at a height (z) (for a mathematical description see Ross, 1981).

Within TF ecosystems the presence of deep canopies (above LAI asymptotic levels) and the great diversity of botanical architectural arrangements are further complicated by the many leaf physiological forms present. In order to facilitate a comprehension of these physiological differences (and their associated reflectance's), the leaf-form adaptations to Richard's (1939) photic strata will be outlined.

The leaves of canopy trees possess many adaptations to the high EMR intensities, and constantly varying humidity conditions, of this stratum. Leaves are generally small and thick and compound leaf structures are abundant. Large spongy mesophyll cells and very large between cell air spaces are also common. These are necessary since  $CO_2$  concentrations are frequently low in the actively photosynthesising canopy. Such features allow canopy leaves to continue to assimilate  $CO_2$  at the high flux densities associated with full sunlight. Canopy leaves are highly efficient in terms of photochemical production, but can dry out quickly at high temperatures. Waxy (water-retaining) derma are therefore common, as are recessed stomata. Despite these adaptations, leaf longevity is comparatively short and leaves are exchanged frequently to ensure optimum productivity. Canopy leaves tend to be held at *planophyll* (horizontally-inclined) angles.

This combination of high photosynthetic productivity and a well developed spongy mesophyll layer results in the contrast between PAR absorption and NIR reflectance being particularly great in this stratum.

Plants in the understorey generally possess large thin leaves which provide a plentiful and easily penetrated light-absorbing surface. Chlorophyll content is high (to allow enhanced light absorption at low irradiance levels). As a result, such leaves are characterised by low photochemical conversion efficiencies. The photosynthetic pigments and pathways of shade species may become saturated at low (e.g. 100  $\mu$ mol m<sup>-2</sup> s<sup>-1</sup>) PAR intensities, which equates to approximately 5% full sunlight. High proportions of chlorophyll- $\beta$  (relative to chlorophyll- $\alpha$ ) further enhance light absorbing capacity especially in the blue-green wavelengths, i.e. between the main red and blue absorbing bands of chlorophyll- $\alpha$  (Figure 2.9). Leaf angle orientation is likely to be at a variety of inclination angles in order to maximise absorption of PAR that has already interacted with canopy vegetation (and been scattered). Leaf surface adaptations to high humidity conditions include elongated ends to leaves, drip tips, and smooth derma.

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Some TF understorey leaves are also articulated to allow sun-tracking positional changes. Heliotropism, the movement of the leaf relative to the solar body, has two major forms: diaheliotropism and paraheliotropism. The movement of blades of diaheliotropic leaves is such that they remain perpendicular to the sun's direct rays throughout the day. The movement of blades of paraheliotropic leaves ensures that their blades remain parallel to the rays of the sun throughout the day. Such movements are achieved in a number of ways. The most commonly observed forms involve twisting the petiole and a pivotal movement of the pulvinus. Diaheliotropism may have a profound impact on the daily rate of net photosynthesis since it allows the sunlit leaf to experience a high solar irradiance throughout the day. Such tracking abilities are independent of photosynthetic pathway and taxonomic affinity. Enhancement of the total received incident radiant flux in diaheliotropic versus horizontal (planophyle -canopy) leaves is c. 40%. In comparison to vertical erectophyle understorey leaves a 170% advantage is gained (Ehlerlinger and Forseth, 1980; Yoda, 1974). Such leaf adaptations have only been noted in the understorey, where water stress is less common. This is unsurprising since a water deficit (common in canopy leaves), would lead to insufficient water to maintain the turgor pressure necessary for the leaf movement mechanism. These movements of leaves in relation to the sun are especially common in the Leguminosae.

In general, understorey leaves have a longer average life duration than canopy leaves. The high building and maintenance costs, associated with larger leaf sizes and greater pigment concentrations, dictating that these leaves are senesced less readily than canopy leaves.

In summary tropical leaf forms reflect their primary purpose, energy partition and conversion. However, the differing environmental conditions associated with TF strata dictate the size, orientation, pigmentation, duration strategies and therefore reflectance of TF strata will vary greatly. The exact nature of this variation is unknown.

#### 2.5.3 Tropical forest gaps

TFs are not static formations of vegetation, but dynamically shifting mosaics of patches (Whitmore *et al.*, 1966). Gaps in the forest canopy are important since the diverse microenvironments created are vital for the regeneration of many TF species. Soil, air temperature, nutrient availability, water balance and light environment all vary as a function of gap size (Denslow, 1980). Whitmore (1992) and Reading *et al.*, (1995) all note that gaps

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may make up a significant part of the forest area. The frequency and size of such gaps perhaps being specific to, or even characteristic of, a TF formation (Denslow, 1980; Hartshorn, 1980; Brokaw, 1982; Swaine and Hall, 1988, Hubbell and Foster, 1986; Canham, 1988; Chazdon

and Fetcher, 1984a; Chazdon and Fetcher, 1984b) (Table 2.9). These gaps typically represent an area of between 0.01 and 0.1 hectares, and are usually caused by the death (and fall) of a tree (Plate 2.4). Whitmore (1990) and Bormann (1953) describe three gap phases: (i) creation; (ii) regeneration, and (iii) maturity. The relevance to this study is that each phase may be characterised by a particular vegetation type. For example, during the regeneration phase, the gap environment is very similar to that of the top of the canopy (without the wind), gaps tend therefore include not to understorey vegetation. Instead pioneer species and gap specialist vegetation dominate. The spectral reflectance of the gap is therefore



Plate 2.4 TF Tree fall

likely to be different to that of the surrounding forest: firstly, in terms of its vegetative reflectance; and secondly, in terms of the amount of soil and litter; and, the contribution of shadow components (Gerard and North, 1997), to integrated reflectance. Gaps may also have a distinct phenological stratagem (Ng, 1981).

Country	TF	Area Studied (ha)	Mean gap size (m <sup>-2</sup> )	Reference		
Ivory coast	Lowland	71	55	Jan <i>et al.</i> (1993)		
Panama	Lowland	28 ,	86	Brokow (1982)		
Panama	Lowland	12	93	Hubbell and Foster (1986)		
Costa Rica	Lowland	12	93	Hartshorn (1978)		
Costa Rica	Lowland	9.7	•	Hartshorn (1989)		

Table 2.8 Comparison of TF gap sizes, after Jans et al. (1993)

## 2.5.4 Integration of TF 'landscape' components

Tropical forests are, complex spatial mosaics, heterogeneous at all spatial scales. The IFOV of any remote sensing system (including the eye) will always represent therefore an integration of many landscape components (e.g. leaves, branches, vegetation architecture, gaps, litter, soil, shadow, standing water). At a large area scale (i.e. >1 km), these reflectance integrations are imposed upon a more gradual ecotonal variation (e.g. those based on topographic-, micro-climatic-, lithological-, and pedological-conditions; flooding regimes, environmental perturbations and landscape disturbance histories) (Whitmore, 1992). Furthermore, the affects of adjacency will result in not only reflectance emanating from the IFOV, but also surrounding areas, contributing radiance to the received signal (Myneni *et al.*, 1992a).

So which reflectance components are the most important at a large area scale? Further, which of these components would it be practical to monitor? Nilson and Peterson (1991) suggest modelling integrated reflectance as weighted by the areal proportions of the individual reflective elements. Huete *et al.* (1992) note that the smaller the leaves of a canopy the greater the influence of substrate in integrated reflectance. Both these observations provide a useful starting point. The canopy stratum is the first layer to intercept EMR, its areal extent, density and leaf size will therefore determine:

- (i) initial reflection; and
- (ii) how much residual radiation is left to interact with the other landscape components (Roberts *et al.*, 1990).

So what parameters best describe these canopy attributes? LAI, LAD and some quantification of percentage cover (Warren-Wilson, 1965) were suggested above (cf. section 2.5.2) and have the advantage of being standardised parameters with associated monitoring techniques (cf. section 2.7). Some consideration of solar and view geometry would also be useful. These potential contributions to the integrated reflectance, in an idealised TF landscape, can then be divided into:

- (i) chlorophyll content (determining PAR absorbing capacity);
- (ii) LAI (determining both the PAR absorbing capacity and NIR reflectance);
- (iii) canopy openness and LAD (determining both the PAR absorbing capacity and NIR reflectance, and, the quantity of other landscape components contributing to the integration); and
- (iv) solar and viewing geometry (determining the proportion of shadow and substrate in the integration).

After interacting with the canopy, subsequent layers of vegetation are encountered. Each of these may also contribute to integrated reflectance and each may also be quantified in terms of attributes (i) to (iv). Lastly, the nature of the substrate (soil, litter, water and / or bare rock) will be important (Scurlock and Prince, 1993).

# 2.5.5 Temporal variations in vegetative reflectance

At the leaf scale, pigment concentration, mesophyll cell orientation and leaf hydration are dependant not only on plant species but also on seasonal developmental stage. Gates and Tantraporn (1952) cite increases in chlorophyll concentration as leaves grow and mature, and decreases in chlorophyll concentration associated with leaf senescence (chlorosis). These leaf pigmentation changes may be extremely rapid (i.e. a few hours) (Daughtry and Biehl, 1985; Jacquemoud and Beret, 1990). During the initial stages of senescence, dehydration causes internal leaf volume to decline and the number of cell interfaces increase. This results in a rise in NIR scattering and hence reflectance. As further dehydration occurs, cell walls split and reorientate themselves; further increases in NIR reflection may result. In the later senescent stages, cells collapse completely and form a series of horizontal layers. The general effect is that reflectance in the red wavelengths increases, whilst NIR reflectance falls (Knipling, 1970; Rock, 1982; Rock *et al.*, 1988). Brakke *et al.* (1993) demonstrate that the directional scattering of leaves is also a function of phenology. Reflectance becomes more diffuse during senescence as chlorophyll absorption decreases and the diffuse reflective component becomes more dominant (due to increased multiple scattering within in the leaf).

At a large area scale, temporal variations in TF reflectance may be divided into six domains (Figure 2.11):

 (i) fluctuations with a duration of seconds, e.g. wind causing leaf flutter (changing the LAD of individual leaves);

- (ii) fluctuations with a period of minutes, e.g. the movement of broken clouds causing an alternation of sunflecked and shaded areas;
- (iii) fluctuations with a period of hours, e.g. a change in solar altitude (diurnal variations);
- (iv) fluctuations with a period of days, e.g. changes in chlorophyll concentration and leaf area (rapid leaf flushing or abscission);
- (v) fluctuations with a period of weeks, e.g. large changes in leaf area, chlorophyll concentration, canopy openness and architectural-structural changes; and
- (vi) fluctuations with a period of months, e.g. profound changes in LAI, canopy openness and the growth (or abscission) of branches. The entire lifecycles of monocotyledonous plants.

Since phenology is a seasonal lifecycle response, only (iv) to (vi) are relevant here. The biological reflective components identified as principal in integrated reflectance (cf. section 2.5.4) (e.g. canopy openness, LAI, LAD, and chlorophyll content) all vary as a result of plant phenological stage.

Although, TF vegetation have pronounced physiological adaptations to the differing abiotic environments found within a forest formation (e.g. canopy - understorey - gap), an argument can be made, to consider the vegetation of each of these respective environments specialist at least in terms of photosynthesis. A hypothesis that each stratum may respond, to the seasonally variant abiotic changes, with a unique phenology seems plausible. This has several consequences for subsequent discussions, and methodologies.

Firstly, any spectral remote sensing technique will monitor an integration of phenological stages:

- (i) from the many different canopy trees; and
- (ii) from a seasonally variant integration resulting from two or more TF strata. At any one time, these strata may be advanced, lagged or synchronised with one-another.

It is necessary, therefore, that any quantification of biological phenology monitor spatial variations at: (a) multiple points within each stratum (especially the canopy), and (b) monitor each stratum separately.

## 2.6 TROPICAL FOREST PHENOLOGY

This section reviews four themes. Firstly, the general leaf flushing, senescence and abscission stratagem of TF vegetation are documented (section 2.6.1), and their flowering (antithesis) and fruiting tactics detailed (section 2.6.2). Next the factors that initiate (and control) TF phenological processes are summarised and the contribution of external (environmental / abiotic) stimuli and internal (biotic) mechanisms to seasonal lifecycle events are evaluated (section 2.6.3). Lastly, the seasonal changes of canopy (and understorey) leaf area and pattern are examined in the context of earth observation (section 2.6.4).

## 2.6.1 Leaf flushing, senescence and abscission

From the paradigm of remote sensing leaf flushing, senescence and abscission are clearly important components of TF spectral phenology. Leaves are the primary production elements of the ecosystem and their presence / absence and condition will affect integrated spectral reflectance in a profound way. The process of growth, senescence and abscission is similar in all leaves (independent of taxonomic affiliation or stratum specialisation), i.e. it is controlled by the plant hormone *abscisic* acid (which regulates abscission); and the hormone *auxin* (which promotes growth). However, the timing, and synchronisation, of the flushing, senescence and abscission events is diverse in TF vegetation.

TF vegetation may renew all or some of their leaves periodically, the degree of synchronisation in the emergence of new leaves (flushing) and the fall (abscission) of older leaves varying greatly (Medway, 1972; Whitmore, 1990). Three generalised patterns of tropical leaf-flushing have been observed in the humid tropics (Frankie *et al.*, 1974; Boinski and Fowler, 1989):

- (i) continuous growth, where leaf flush (and fall) occurs throughout the year;
- (ii) intermittent growth, where leaves are commonly flushed over several months; and
- (iii) seasonal growth, where leaves are flushed (and fall) simultaneously.

In the first of these strategies leaves are exchanged, i.e. a new leaf is associated with the abscission of the previous one. Only a few tropical plant species grow in this manner (most commonly in the understorey) and all have long associated leaf lifetimes (Singh *et al.*, 1990; Ralhan *et al.*, 1985a; Ralhan *et al.*, 1985b).

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Intermittent or periodic changes in leaf-production are far more common (Whitmore, 1990). Here leaf flushing (and fall) are not fully synchronised, either with regard to season, species or individuals (Pires and Prance, 1985). As a consequence, such trees do not affect the evergreen nature of the canopy as a whole. This leaf production strategy is associated with humid evergreen TF formations where environmental resources exhibit very little seasonality.

The synchronous flushing of new leaves occurs in (semi-) deciduous species. These shed their leaves well before bud-break and so have a bare crown for as long as a few weeks (Longman and Jeník, 1974; Whitmore, 1990). All TF formations contain some tree species which exhibit deciduous (or semi-deciduous) behaviour. These trees show a greater (proportional) loss of leaf mass, and this is highly correlated with stem shrinkage and seasonal water deficits (Boaler, 1986; Daubenmire, 1972; Borchert, 1980; Ralham and Singh, 1987).

Leaf abscission may be characterised in a similar manner to that described for leaf flushing above, i.e. be continuous, intermittent or seasonal. Abscission may be achieved by the shedding of: individual leaves; small twigs (with leaves in place, cladoptosis); or larger (lower-order) branches. These abscission events are always advantageous to the plant representing an adjustment to seasonally changing environmental resource availability (Addicott, 1978). For example, leaves will be shed if they are injured or diseased, have come to the end of their productive life, or to alleviate a plant water deficit.

Abscission in tropical vegetation has been correlated with a number of meteorological and seasonal variables ranging from the purely mechanical removal of senescent leaves by wind or storms (Gosz *et al.*, 1972) to wet season(s), dry season(s) and/or changes in temperature and humidity (Frankie *et al.*, 1974) (Table 2.9).

# Table 2.9 Associations between litterfall and rainfall seasonality

Dry Season Peak	Location of
Beard (1955)	Trinidad
Koelmever (1959)	Sri Lanka
Madge (1965)	Nigeria
Honkins (1966)	Nigeria
John (1973)	Ghana
$\frac{1973}{1974}$	Costa Rica
	Brasilian
Frankie et al., (1979)	Amazonia
Kunkel-Westphal and Kunkel (1979)	Guatemala
Van Schaik (1986) and	Sumatra
Van Schaik et al., (1985)	Sumara
Dantas and Phillipson	Brasilian
(1989)	Amazonia
Honking (1966)	North-east
	Australia
Luizao (1989)	Brasilian
Luizao (1989)	Amazonia
Proctor (1987)	Sabah
Wright and Corneia (1990)	Barro Colorado
wright and Comejo (1990)	Island (Panama)
Scott at al. $(1002)$	Roraima
500t et ui., (1992)	(Brasil)
Proctor et al., (1984);	Sarawak
Proctor et al., (1987)	(Borneo)
Frankie et al., (1974)	Costa Rica
Hopkins (1966)	Nigeria
	an a
Bimodal Peaks	
(Wet & Dry season)	
Cornforth (1970)	Irinidad
Jackson (1966);	Brasilian
Jackson (1978)	Amazonia
No Peak (aseasonal)	Malara
Medway (1972)	Malaya
Putz (1979)	Nalaysia
End of Day Stort of Wet	ana an
Season Deak	
Koelmever (1050)	Sri Lanka
Nicky (1963)	Nigeria
NJOKU (1903)	
Wat Season Peak	oland har stationage with the with the
Medway (1972)	Malava
Meanuy (1972)	Peninsular
Ng (1981)	Malaysia
Van Schaik (1986) and Van Schaik <i>et al.</i> , (1985)	Sumatra
Proctor et al., (1984);	Sarawak
Proctor et al., (1987)	(Borneo)

Table 2.9 compares TF litterfall with rainfall seasonality. A clear trend towards dry season abscission is apparent. Factors such as the incompleteness of review, and attempted correlation with only one meteorological parameter are obvious limitations, nonetheless the association is significant.

Plant water stress was hypothesised by Wright and Cornejo (1990) as the proximal cue for leaf fall in seasonal TFs. This they attempted to prove by irrigating the soil for the duration of the dry season. Irrigation delayed leaf fall in only two of 25 monitored tree species. Water deficit alone therefore appears to have little impact, at least at their experimental site. Daubenmire (1972) and Lieberman (1982) both measured trunk contraction and expansion in an attempt to quantify the importance of water availability, in a seasonal TF. They conclude that many seasonal semi-deciduous tropical trees are phenologicallyopportunistic, i.e. respond rapidly to changes in moisture availability (Lieberman, 1982; Tyrell and Coe, 1974).

Borchert (1980); Njoku (1963); Hopkins (1966); John (1973); Jackson (1978); Boaler (1986); all note good correlation between seasonal water deficit and leaf fall. These authors experienced difficulty, however, in establishing correlation with other phases of TF development, such as leaf-flushing, flowering and fruit emergence.

## 2.6.2 Flowering (antithesis) and fruiting

In general, the timing of the TF flowering phenophase occurs just before the period of maximum (resource) abundance, and the fruiting phenophase during the period of maximum (resource) abundance. This is since TF vegetation must ensure suitable environmental conditions (i.e. those conducive to successful germination and seedling prosperity) are present when fruits are dispersed. Such conditions are generally met during periods of water abundance and high irradiance. If such conditions occur throughout the year, flowering and fruiting are likely to exhibit no seasonal trend (e.g. Figure 2.12 top). Where a dry season is present, flowering will be more seasonal (Araujo, 1970; Alvim and Alvim, 1978). In TFs with a pronounced dry season flowering is often preceded by a leaf fall episode and subsequent rehydration of the vegetation (Reich and Borchert, 1984). This occurs in the Miombo Savanna ecosystem (Table 2.10) where many species flower (and flush) before the rainy season starts (Malaisse *et al.*, 1972; Malaisse, 1974; Frankie *et al.*, 1974; Monasterio and Sarmiento, 1976; Prasad and Hedge, 1986).

		Strata			
Meteorological Season	Canopy	Sub-Canopy	Understorey	Total (no. of individuals in flower)	
Dry	1	3	2	6	
PreRains	5	6	4	14	
Early rains	0	0	1	1	
Main rains	0	0	2	2	
Late rains	0	1	6	7	

Table 2.10 Seasonality of flowering in a Savanna (Miombo) ecosystem, after Malaisse (1974)

Other abiotic factors reported to affect TF flowering include temperature (Umana-Dodero, 1988) and changes in photoperiod of as little as 15minutes (Njoku, 1963).

Most TF trees depend on animals (usually insects, birds or bats) for pollination, employing diverse methods for attracting their pollinators. Common methods include the use of highly scented or brightly coloured flowers. For example, many TF flowering trees flower in the same climatic season but do not overlap their flowering times (Frankie *et al.*, 1974). Such staggering reduces inter-species competition. Pollination systems are often extremely complex, relying for example, on a single insect, whose lifestyle depends, in turn, on other plants or animals. This is the case for the Brasil-nut tree (*Berthoiletla excelsa*) which is pollinated by several species of bee that require certain chemicals produced only by an

epiphytic orchid for mating and reproduction. These orchids are themselves are wind pollinated (Frankie et al., 1974).

## 2.6.3 Abiotic and biotic controls of TF phenology

Phenology, as defined by Leith (1974), is the study of seasonally recurring biological events along with the causes of their timing (and duration) both with regard to biotic and abiotic forces. In this sub-section, the relative contribution of these two agents will be assessed.

Phenological studies are inherently complex, this is especially true within TF ecosystems. The high diversity of life-forms present, the intricacy of their inter-relationships, and the fact that each species may display a unique phenological-response to the changing abiotic environment leads to a bewildering array of phenological patterns. As we have seen, seasonal variations within the tropical meteorological environment (i.e. in temperature, humidity, rainfall, soil moisture, light intensity and spectral composition) will expose a plant to periodic changes in the quantity and quality of these resources. Although the amplitude of variance for individual parameters may be small, taken as a system all tropical environments experience some seasonal variance.

There is a temptation when studying TF phenology to look to one individual meteorological parameter to explain the timing or duration of a phenological stage (see Table 2.9 above and Murphy and Lugo, 1986; Whitmore, 1966; Monteith, 1972; Young, 1975; Smith, 1981b; Lieberman, 1982; Rai and Proctor, 1986; Sellers *et al.*, 1989; Turton, 1990; Whitmore, 1992). Variations in the availability of water (determined by rainfall and humidity levels) being the most frequently invoked environmental cue (e.g. Alvim and Alvim, 1978; Borchert, 1980; Reich and Borchert, 1982; Borchert, 1994a; Table 2.9). However, observed phenological-phase variations (in the timing, duration and intensity of plant seasonal development stages, or phenophases) occur between species but also amongst individuals (of the same species). This intra-species variation is often so profound that observed differences in environmental conditions are insufficient to explain this variance. For example multiple phenophases are sometimes observed on an individual tree (Borchert, 1980). An alternative mechanism for the botanical phenological process is therefore necessary: an endodynamic control.

Within the humid tropical biome, the resources available for vegetative growth may be omnipresent (despite seasonality). The importance of an individual plants' endodynamic processes may play an increased role in the phenological process. Singh *et al.* (1990) and Koike (1990) both note endodynamic biorhythms operating within individual TF crowns. Two types of senescence are cited:

- (i) an *inner-type*, where senescent leaf-colouring develops first in the inner crown first and spreads outward (younger leaves being present at the outer surface of the crowns); and
- (ii) an outer-type, operating vice versa (here leaf age is similar throughout the crown).

These studies are interesting since one must assume that the microclimatic conditions operating within an individual tree crown are very similar. The crowns still exhibited distinct phenological patterns despite the lack of meteorological cues to phenology. Observations of this sort, along with the common lack of direct correlation between the environmental parameters and phenological phases, have been explained as the interaction of internal controls and environmental inputs (Borchert, 1994a; 1994b; Lee, 1989; Pinkker, 1980) (Figure 2.13). Some authors such as (Leigh *et. al.*, 1982) argue that environmental changes may be better conceptualised as signals for phasing, or resetting, endodynamic cycles rather than initiating stimuli. Such a synchronising role for meteorological changes would be most obvious in a seasonal environment (Alvim, 1960).

# 2.6.4 Seasonal changes in canopy and understorey components: a remote sensing perspective

This investigation seeks to understand the connection between spectral and biological phenology. At a large area scale (i.e. > 1 km), seasonal spectral reflectance changes will result from an integration of biological changes in (canopy-understorey-ground mosaic) leaf area and pattern. This section assesses the different leaf phenological-phase differences that may be detected using large area earth observing systems.

A phase difference in leaf deployment may occur between the strata of TFs. This is since each stratum will act to deploy the maximum leaf area possible within the environmental constraints placed upon it (i.e. the availability of water and PAR). Where such resources are aseasonal leaf phenology will be evergreen. In a more seasonal climate, the canopy stratum may open-up significantly (or at least thin) during a dry period. In the lower photic-stratum leaf deployment and replacement are more irregular and semi-independent of exodynamic

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processes. Here individual plants and indeed even branches (on the same tree) may be phenologically lagged or out-of-phase with one another. In the words of Medway (1972) and Putz (1979) they lack 'community phenology'. Any remotely-sensed spectral phenology will represent a 3-dimensional integration of all these phenophases.

# Summary:

There is a clear need to monitor the potential abiotic triggers to TF phenology, particularly meteorological parameters with hydrological components. When analysing these data the degree of abiotic control on TF vegetation phenology, is expected to increase with the degree of deciduousness of the TF formation and to be greatest in the canopy layers of the forest.

The leaves of dicotyledonous plants are better adapted to seasonally varying abiotic conditions than those of monocotyledonous plants. Senescence of the dicots is easier to achieve This is since the point of leaf attachment in dicots is the base of the petiole. When compound leaves are present, a rapid shedding of leaves is possible by abscising this single point. In most monocot plants, the petiole is lacking, and the base of the leaf is a broad, flat sheath wrapped around the stem. Abscission in response to high evapotranspirational losses is therefore difficult or impossible to achieve. The distribution of dicot : monocot both between strata and TF types is interesting since the most seasonal elements of all strata are the dicots. This supports Sinclair *et al.*, (1972) hypothesis that each discrete layer of the tropical forest has a generalised cell structure.

The integrated response as observed by remote sensing requires further investigation. This can only be attempted by studying the phenological phase differences and associated reflectances of several TF strata simultaneously.

## 2.7 GROUND MONITORING AND FIELD RADIOMETRY

This section reviews the techniques for monitoring biological phenological change. It is presented in three parts. The first (section 2.7.1) addresses the general methodological considerations that arise when undertaking long-term environmental monitoring. Next, an assessment of various techniques for quantifying vegetation amount and condition is undertaken (section 2.7.2). Lastly, the theory and operation of spectral radiometers is detailed (section 2.7.3).

### 2.7.1 Methodological considerations

Munn (1970) identified the principal sampling problem in experimental science as the separation of signal from noise. In the context of this research, this problem is two-fold. Firstly, the biological phenological parameters, selected for monitoring, need to be spatially sampled in a manner that is meaningful for comparison to a large area remotely sensed dataset. Secondly, they must be sampled at a temporal frequency that is both logistically possible and scientifically meaningful.

Many different reflectance components are potentially represented within a single remotely sensed pixel (cf. section 2.5.4). The practicality of monitoring these variables (e.g. canopy openness, LAI, LAD, and chlorophyll content) is subject for the next section (2.7.2). But how frequently should they be sampled and for how long?

TF phenological changes occur on a time-frame of days to months (cf. section 2.5.5) and have an implied annual periodicity. The total length of a phenological study would logically be therefore a multiple of a terrestrial year. During this time, the continuous acquisition of data would be ideal but data volume and time / technological considerations may prevent this (especially if the phenology of more than one TF formation is to be monitored). Once these measurements are obtained, an averaging (time) period(s) needs to be defined Again, this would logically would be a fraction of a terrestrial year, i.e. months (12), weeks (52) and certainly days ( $365^+$ ). But which is most appropriate? The concept of *alaising* (a mathematical term) is illustrated on Figure 2.14. Here clearly the temporal sampling (or composite) frequency will radically change the observed trend in a time-series data. This time-sampling problem is critical in environmental studies, since in the time domain, there is almost always difficulty in deciding whether individual points are in fact members of the same population.

This is particularly the case with phenological data since the response-rhythms and time-lags are not known. Too close a temporal sampling regime may introduce noise; too wide spacing on the other hand may result in the partial loss of signal.

The reality of field science dictates however that logistical constraints of movement between field sites as well as ideal scientific goals will determine the sampling frequency. Observations that are required very frequently, i.e. on a daily basis, will have to be achieved through the use of automated procedures.

## 2.7.2 Assessing vegetation amount and condition

Assessing a plant's (or vegetation stratum's) phenological stage is a complex process. The massive TF phenological literature provides little detailed information on the practicalities of phenological observation and measurement in TF environments (Schirone, 1990). Whilst many studies do contain qualitative observations, this research has a clear need for quantitative data. In section 2.5.4, several vegetative parameters (e.g. LAI, LAD, chlorophyll content and canopy openness) were identified as crucial to integrated spectral reflectance. All of these will also vary as a function of biological phenology (section 2.5.5). But, how successfully can they be monitored? Techniques are required that are quick, accurate and can be achieved with what MacDougall and Kellman (1992); Munn (1970); Idrac (1968) have all termed finesse. This last attribute is the ability of a technique to monitor a parameter of interest without causing modification to the environment by its very existence.

The simplest way to obtain information about leaf area and orientation is to measure it directly. Three basic strategies exist. The stratified clip method, the dispersed individual plant technique and the inclined point quadrat.

The stratified clip method is usually undertaken on small plants such as grasses. I involves the demarcation of a rectangular (or circular area) within which all foliage is cut. The vertical distribution of foliage can be obtained by clipping horizontal layers separately. The foliage elements are subsequently measured using:

(a) automatic planimeters;

(b) area leaf dimensions;

Area = k (length x maximum width) 
$$[2.5]$$

the coefficient k is 0.75 for grasses; 0.66 for many dicot vegetation leaf forms; (Ross, 1975; Ross, 1981); and / or

(c) leaf area to weight regressions.

The application of this technique to larger vegetation has been attempted, e.g. thorough the use of regression (allometric) equations developed between the leaf area measurements and inventory data (such bole cross-sectional area per ha<sup>-1</sup>). The advantages of this technique are that it is comparatively quick and that that it fits easily into a sampling framework. Its disadvantages are that systematically carrying out repeated measurements (of TF trees for example) would not be realistic.

The dispersed individual plant method involves detailed measurement of individual plants. Direct measurement of both LAI and LAD are possible. These are exceedingly time consuming and fraught with potential errors (for a review see Ross, 1981). Lewis (1995) developed a photogrammetrical technique for such measurements but again is extremely timeconsuming although less destructive.

The potential use, to phenological studies, of these two techniques is therefore very limited.

Warren Wilson (1963) described an inclined point quadrat. This involves the insertion of a probe into the canopy at a known inclination and azimuth angle. The number of point contacts with leaves and stems is then calculated. Point quadrat records may then be expressed as:

- (i) LAI (all contacts through the depth of the canopy are scored; this yields the mean number of contacts per quadrat); and/or
- (ii) percentage cover (only the first contact made by the quadrat is scored, subsequent contacts being ignored).

This method has been adapted to forests as the drop-line method. Its principal problems include a lack of finesse (an inability to observe the probe without disturbing the canopy) and expense in terms of time and logistics. Its use as a monitoring tool is therefore very limited.

Chlorophyll content, no simple field method exists for measuring the chlorophyll content of a canopy without destructively sampling large areas. Instead many researchers (e.g. Odum *et al.*, 1963; Leigh, 1975) have proposed that litterfall and leaf fall may be monitored and leaf area losses inferred.
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Measurements of percentage canopy cover (or openness) can most easily be achieved using hemispherical photographs. The technique of hemispherical photography was introduced to Ecology about 30 years ago (e.g. Evans, 1956; Evans and Coombe, 1959; Evans, et al., 1960; Grubb et al., 1963; Anderson, 1964a; 1964b; 1964c; Rich, 1990). Photographs are usually taken looking upwards from within a canopy (Chazdon and Field, 1987a; 1987b; Becker and Erhart, 1988; Rich, 1990) using an extremely wide angle lens. This hemispherical lens produces an image that is a projection of the hemisphere on a 2-dimensional plane. A circular image is typically produced, with the zenith at the centre and the horizon at the edges. Any point within the hemisphere may be defined by a unique zenith angle ( $\theta$ ) (angle between the zenith and sky direction) and azimuth angle ( $\alpha$ ) (the angle measured counterclockwise from north to the direction of sky direction). For a fuller account see Rich (1990) and Herbert (1987). Hemispherical photographs allow a quantification of the distribution and intensity of light reaching a particular point under the canopy. Estimations of the direct light component may be made using solar track diagrams, whilst diffuse light may be calculated using a 'spiders web' grid. This divides the photograph into areas in receipt of equal amounts of radiation. The estimated percentage of un-obscured sky in each annulus can then be calculated. Repeat observations from the same camera positions allow seasonal changes in foliage area densities to be documented.

# 2.7.3 Radiometers, theory and practice

The coupling between radiation exchange and canopy structure is so strong that measurements of radiation may be used to infer canopy features. This relationship forms the basis for several indirect measurement techniques (Norman and Campbell, 1989; Chazdon and Field, 1987). Such methods usually involve the measurement of radiation attenuation (from within a vegetation canopy, *Ceptometry*) or radiation reflectance (*radiometry*). Data from these measurements are then combined with an appropriate inversion of a radiative transfer model, or converted to reflectance measurements to derive an estimation of biophysical parameters (Welles, 1990; Clark and Follin, 1988).

As early as 1916 Salisbury was studying light as an ecological factor in forests. This he achieved by comparing photosensitive paper exposed in clearings and in the understorey. Research into the interaction of EMR with tropical forests also has a long history (e.g. Evans,

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1956; Whitmore and Wong, 1959; Evans *et al.* 1960; Whitmore, 1966; Brinkman, 1971; Richards and Williamson, 1975; Honda and Fisher, 1978; Formann and Hakhn, 1980; Chazdon and Fletcher, 1984; Turton, 1988). More recently, analyses of seasonal variation in the light climate have also been undertaken (Canham *et al.*, 1990; Pearcy, 1988; Torquebiau, 1988). All these studies have centred on characterising the quantity and spectral quality (and spatial distribution) of light reaching the forest floor. They all emphasise the extreme spatial and temporal variability in TF light environments. In this study a characterisation of TF light environments is not required, rather a quantification of seasonal reflectance changes in the vegetation components is necessary.



Plate 2.5 Radiometer in operation (courtesy NASA, Goddard Space Flight Centre)

Ground based radiometers monitor changes in reflectance in a manner similar to the spectroradiometers carried onboard satellite remote sensing platforms. The principal difference being that, whilst a remote sensing radiometer typically acquires an image of reflected values (using an array of detectors, or a scanning a mirror, to collect sequential samples from different ground areas); a radiometer occupies a static ground based position and acquires a single measurement (per wavelength) of the target area (Plate 2.5).

Reflective measurements are usually acquired by means of a small detector that collects upward welling radiance from a given solid angle (or cone). The detection device is usually photoelectric cell (e.g. silicon) which consists of a small chip that is sensitive to EMR. This functions by absorbing photons, which cause a release of electrons and the generation of an electric current in direct proportion to the photon flux. Such measurements have long been used to validate remotely sensed data, indeed most remote sensing instruments have associated radiometers that mimic their spectral and radiometric idiosyncrasies (e.g. the MSS and the Milton multi-band radiometer, Milton, 1980; 1987). The big advantage of radiometry is that the measurements are integrated. They are ideal therefore for comparison too remotely sensed spectral data. Their big disadvantage is that the biological significance of the derived reflectance values is again difficult to establish since they represent spatial integration of all the reflectance components in their field of view (FOV).

The ideal radiometer would give accurate readings over a wide range of illumination conditions; have a good cosine response (i.e. obey Lambert's Cosine Law and not be sensitive to EMR from a particular direction) and sample multiple points simultaneously to allow spatial variations both between TF strata and within individual stratum to be characterised (cf. section 2.5.5). Salminen *et al.*, (1983) recommend the following:

- (i) the primary factor is that the radiometer should always view the same reflectance target;
- (ii) the acquisition time of a reading should be less than the time required for changes to occur in the irradiance conditions (cf. figure 2.11);
- (iii) the number of measurement points should be large enough to permit the study of spatial variation;
- (iv) a good radiometric sensitivity; in the context of monitoring TF vegetation a broad dynamic range of reflectances should be expected.
- (v) where more than one sensor is used, sensors need to be calibrated relative to each other by pointing them at a grey card target (such as Barium sulphate) illuminated by a constant source (Jordan, 1969; MacDougall and Kellman, 1992).

Any radiometry system, designed for large area phenological monitoring should:

 (i) simulate the wavelengths, and band-pass widths, of the satellite sensors used in the study; (so spectral reflectances of remote sensing systems (and derived phenologies) can be better understood).

- (ii) monitor reflectance and irradiance at times synchronous with the satellite overpasses
   (to minimise illumination angle differences i.e. in shadowing, bidirectional reflectance, look angle and illumination geometries);
- (iii) be easy to install and maintain, and ideally be user-designed, (Bingham and Long, 1993);
- (iv) be robust and environment proof, (Szeicz, 1975; Szeicz, 1968);
- (v) sample numerous points simultaneously (Evans, 1956) to facilitate an understanding of the variations in reflectance-components which are integrated at a 1 km scale.

# 2.8 REMOTE SENSING IN PHENOLOGICAL STUDIES

This section aims to review remote sensing in the context of large-area phenological monitoring. Specifically, its objectives are: (i) to introduce the satellite-sensor combinations used in this study, namely ERS-2 ATSR-2 and NOAA-14 AVHRR (section 2.8.1); (ii) to review the use of Vegetation Indices (VIs) and Principal Component Analysis (PCA) (sections 2.8.2 and 2.8.3) in spectral phenological studies; and lastly (iii) to review past research centred specifically on spectral phenology in a TF context (section 2.8.4).

# 2.8.1 Satellite instrumentation and sensor characteristics

This study makes use of the European Space Agency Along Track Scanning Radiometer-2 (ATSR-2), aboard the ERS-2 satellite (launched in May of 1995, Plate 2.6); and the AVHRR instrument (aboard the NOAA-14 satellite, operational dates: Dec. 30, 1994 until present).

The ATSR-2 is a passive, dual view (nadir and  $55^{\circ}$  forward-looking), self-calibrating, radiometer. It observes the Earth's surface along two curved swaths at a nominal spatial-resolution of 1 km<sup>2</sup>. Both swaths are c. 500 km wide, the two views being separated by a c. 900 km along-track distance. In the nadir view, scan line-centre pixels are exactly 1 km x 1 km in dimension, whilst in the forward scan, line-centre pixels represent a larger area of c. 1.5 km x 2 km. Because of the conical scanning motion of ATSR-2, the ground position of the IFOV moves considerably during the acquisition time (the centre of the IFOV being 'observed' for longer periods than the edges). The centres of the ground resolution elements at

nadir and forward scans do not therefore coincide and the forward scans are re-sampled to fit the nadir scan geometry. The forward and nadir looks therefore sample different ground areas. The characteristics of the sensor are detailed in Table 2.12. For further details see Bailey (1995).



Plate 2.6 ERS-2 Satellite and the position of ATSR Instrument

The Advanced Very High Resolution Radiometer has a long and distinguished service history (of over 20 years). The latest incarnation (NOAA-14) has been in (almost uninterrupted) service since 30 December 1994. During this time, the AVHRR instrument has become the staple for the large area observation of Earth surface processes. It is characterised by a wide instrument scan (+/-55.4° nadir) resulting in a swath of c. 2700km. This enables very frequent (off-nadir) coverage for any given geographical position. Considerable changes in the spatial resolution of the imagery occur however (depending on the position of the pixel within the scan line). This may vary between 1.1 and 1.2 km<sup>2</sup> at nadir to 15.6 km<sup>2</sup> for pixels at extreme off-nadir positions (Goward *et al.*, 1991). Off-nadir viewing also results in changes in atmospheric modulation along the scan line (twice the optical air mass being traversed by the target-sensor vector at the extreme viewing angle than at nadir, Holben and Fraser, 1984).

Atmospheric correction is an essential prerequisite for any long term environmental monitoring. This is because variations in reflectance from one date to the next may result

# CHAPTER 2, Literature Review

from changes in the atmospheric optical thickness and not from 'real' variations in groundreflectance. In studies using multi-temporal data, this can create serious errors (Duggin and Piwinski, 1984). This is particularly the case for phenological studies with their implied long time-series. Most atmospheric correction procedures are in agreement for solar and view angles less than c. 60-degrees. The proper use of the atmospheric correction code is therefore of more concern than which code to use. For a full description of the available methods and potential problems see Teillet (1992); Moran *et al.*, (1992). These issues are also addressed in section 4.2.1. For a full description of the sensor characteristics see Kidwell (1991); Sader *et al.*, (1990b); Lloyd (1990); Popham (1988) or NOAA (1998).



Plate 2.7 The ATSR-2 Instrument

Characteristics	NOAA-14 AVHRR	Potential in Vegetation Monitoring	ERS-2 ATSR-2	Potential in Vegetation Monitoring
Orbit	Sun-synchronous		Sun-synchronous	
Equatorial Crossing Time	c. 13:40		c. 10:15	
Channel 1	0.58-0.68 µm	~	0.545-0.565 μm	1
Channel 2	0.735-1.1 μm	1	0.649-0.669 µm	1
Channel 3	3.55-3.93 µm		0.855-0.875 μm	1
Channel 4	Channel 4 10.3-11.3 µm		1.58-1.64 μm	~
Channel 5	11.5-12.5 μm		3.55-3.93 μm	a design to referre
Channel 6	×		10.4-11.3 μm	
Channel 7	×		11.5-12.5 μm	CARA CONT
Radiometric Quantisation	10 bit (1024 levels)		12 bit (4096 levels)	
IFOV (dimensions at Nadir) Centre Pixel	1.1 km		1 km	
IFOV (Forward) -Centre	Absent		1.5-2 km	
Swath Width	c. 2700 km		c. 500 km	
Dual view	Absent	55° Forward		
Radiometric Calibration	Absent		Present	

Table 2.11 Comparison of ATSR-2 and AVHRR

## 2.8.2 Spectral vegetation indices

Spectral vegetation indices (VIs) are by far the most popular tools used to analyse remotely sensed spectral reflectance data from vegetation. These indices exploit the fact that live green vegetation absorbs radiation in the visible wavelengths and strongly scatters solar radiation in the near-infrared wavelengths (cf. section 2.5). VIs are normally orthagonally-based, or ratioed, combinations of these wavebands. For example, the simple ratio vegetation index (RVI, Jordan, 1969; Tucker, 1979) quantifies vegetation amount as:

$$RVI = NIR_{o} / RED_{o}$$
 [2.6]

An alternative VI, proposed by Rouse *et al.*, (1975), and widely adopted, namely the normalised difference vegetation index (NDVI), today provides the mainstay of long-term datasets for environmental monitoring.

$$NDVI = (NIR_{0} - RED_{0}) / (NIR_{0} + RED_{0})$$
<sup>[2,7]</sup>

Other common combinations include orthogonally transforming the index as a deviation from a theoretical soil line or point (Figure 2.15) (e.g. Kauth and Thomas, 1976; Huete *et al.*,

1992; Pinty and Verstraete, 1992a). Such indices include the GVIs (Greenness-VIs, Kauth and Thomas, 1976) and the Perpendicular Vegetation Index PVI (of Richardson and Wiegand, 1977). This last index calculates the departure of growing vegetation from a soil reference vector (r). The result being (semi-) independent of soil type.

$$PVI = \sqrt{\left[\left(\rho_{soil\_red}} - \rho_{vegetation\_red}\right)^{2}\right]} + \sqrt{\left[\left(\rho_{soil\_NIR}} - \rho_{vegetation\_NIR}\right)^{2}\right]^{[2.8]}}$$

or

$$PVI = \frac{[a_i - \text{Re}\,d + a_0]}{[1 + (a_i)^2]^{1/2}}$$
[2.9]

Where:

a<sub>0</sub> is the soil line intercept,

a<sub>i</sub> is the slope of the soil line,

the index is therefore the orthogonal distance from the soil line.

Huete (1988) also proposes a VI that attempts to compensate for the effects of soil, the Soil Adjusted VI (SAVI) (see section 6.2.1, equation 6.1). Here a correction factor L is introduced and has been demonstrated to minimise the reflection contributions from the soil-substrate (Huete *et al.*, 1992). Baret and Guyot (1991) present a Transformed Soil Adjusted VI (TSAVI) which compensates also for atmospheric effects (Pinty and Verstraete, 1992a).

$$TSAVI = \frac{a_i(NIR - a_i(\text{Re}\,d) - a_0)}{[\text{Re}\,d + a_i(NIR) - a_i.a_0]}$$
[2.10]

Where:

a<sub>0</sub> is the soil line intercept,

 $a_1$  is the slope of the soil line,

the index is therefore the measure of the angle between the soil line and a line joining the vegetation point with the soil line intercept.

VIs are however very sensitive to a number of other environmental parameters, notably; sun-sensor geometry (Qi *et al.*, 1994), sensor characteristics (Elvidge and Chen, 1995), instrument precision and calibration (Goward *et al.*, 1991), the proportion of diffuse irradiance and cloud contamination (Gutman, 1991; Pinty and Verstraete, 1992), LAD and topographic effects (Holben, 1986). Many researchers have developed atmospherically insensitive VIs in an attempt to counter some of these problems e.g. the ARVI (Atmospherically Resistant Vegetation Index, Kaufman and Tanré, 1992) and the GEMI (Global Environmental Monitoring Index, Pinty and Verstraete, 1992b). The later these being based on a non-linear combination of AVHRR channels 1 and 2 (see section 6.2.1, equations 6.2 and 6.3). Its authors report the GEMI to be less sensitive, to atmospheric effects, than other VIs, so minimising the dependence on complex atmospheric correction algorithms in long term environmental monitoring.

Although no universal relationship between VIs and biological parameter(s) can be stated, statistically significant correlations have been found between VI's and a wide range biophysical factors; green leaf area index (Jordan, 1969), biomass (Asrar *et al.*, 1989), absorbed photosynthetically active radiation (Goward *et al.*, 1985), LAI (Justice *et al.*, 1985; Asrar *et al.*, 1984; Asrar *et al.*, 1989; Peterson *et al.*, 1986), actual transpiration (Wellens, 1997), percentage green vegetation cover and chlorophyll content (Colwell, 1974; Lillesand and Kiefler, 1987; Justice *et al.*, 1989; Achard and Blasco, 1990; Pinty and Verstraete, 1992; Derrien *et al.*, 1992; Millington *et al.*, 1994; Myneni *et al.*, 1997). The association between botanical phenology and temporal variations in VIs is then well established. For example, the seasonal development of vegetation is mirrored in a hysteresis loop (within red - NIR feature space, figure 2.16) (Tucker, 1979). An extensive review of the retrieval of biophysical parameters from satellite imagery (using VIs) can be found in Asrar *et al.* (1989).

#### **2.8.3** Principal components analysis

The application of principal components analysis, to spectral phenological studies, has been widely attempted at many spatial scales from the regional to the continental (e.g. Justice *et al.*, 1985; Lloyd, 1990; Achard and Blasco, 1990; Derrien *et al.*, 1992). Its main advantage is as a data reduction tool, whereby individual spectral channels and image dates may be combined into a single seasonality index. The methodology of Tucker *et al.* (1985) is typical

of most in the TF paradigm. Here a principal component (PC) transformation is undertaken on a time-series of NDVI images and a feature space plot of the first two PCs examined to derive a land cover classification. Taking Tuckers' example, eight (3-week composite NDVI) images would be transformed (a total of 48 AVHRR spectral channels) into a single index. The n principal components are then related to their original values by:

$$P_i \sum a_{ij} NDVI_j$$
<sup>[2.11]</sup>

Where,

i=1,8

j=1,8

and  $a_{ij}$  are the eigen vectors ranked in order corresponding to the size of the eigen values. Each eigenvector represents the relative contribution of each respective time period to the principal component. The first PC typically has near equal eigenvector weightings, for all the time periods (representing an integration of all of them). The second PC typically shows a quasi-sinusoidal structure (and represents the seasonal elements of spectral reflectance).

#### 2.8.4 Remote sensing of phenology and tropical vegetation studies

The use of an aerial *synoptic* overview in phenological investigations has long been realised. For example, Olson and Good (1962) and Gammon and Carter (1979) both monitored (relatively small) ground areas by employing time-series of aerial photographs. The advent of satellite-derived data (especially from the Landsat-series satellites) allowed a much longer, more consistent and cheaper, multi-temporal archive of phenological data to be examined (e.g. Rouse *et al.*, 1974; Ashley and Rea, 1975; Honey and Tapley, 1981). This data had the added advantage of systematically surveying much larger areas. Typical of such early investigations is that of Dethier (1974) who conducted the first *'phenology satellite experiment*' using the then Earth Resources Satellite (Landsat-1) Multi-Spectral Scanner (MSS) instrument. Observation of indicator species (set within a phenological-observation network) allowed spectral changes to be associated with vegetation senescence and development to be documented. Dethier concluded, that a temporal frequency of 3 days was optimal for phenological monitoring and therefore the 18/16-day temporal resolution of the Landsat series satellites was inadequate.

Since the mid-1980's, there have been numerous attempts to monitor TF phenology using remote sensing. Justice et al., (1985); Tucker et al., (1985); Townshend et al., (1985), suggested the best available satellite-sensor configuration to study regional and global scale phenological processes was the AVHRR. Observations using AVHRR-GAC, and GVI, products provided a much improved temporal resolution. Temporal gains were however at the expense of subsequent losses in both spatial resolution (to 4 km<sup>2</sup> and 15 km<sup>2</sup> respectively) and data integrity (due to the NOAA on-board re-sampling scheme, see Justice et al., 1989, for a full review). This trade-off of spatial resolution to acquire temporal frequency has enabled global spectral phenology to be studied using GAC-data since 1979 (Gatlin et al., 1983) and using GVI (Global Vegetation Index, IFOV 15 km at the equator) products since 1982 (NOAA, 1983; Tarpley et al., 1984). But how representative of biological phenology are these spectral indices? Goward et al. (1991; 1994) credit AVHRR derived monthly estimates of global vegetation dynamics, with an error of +/-10 %. Townshend and Justice (1986) note however that some areas (particularly TFs) suffer from persistent high cloud cover prohibiting the acquisition of a sufficient number image-dates to allow an accurate phenological characterisation.

Modifications of the PC technique (cf. section 2.8.3) have been used to map the vegetation cover of South America, and many other TFs world-wide (Justice et al., 1995, and Stone et al., 1994). For example, Townsend et al. (1987) took the highest weekly NDVI for each month and averaged it into three monthly values to minimise the effects of cloud contamination and probable inter-annual mis-calibration and radiometer drift. These studies demonstrated that TFs exhibit a high NDVI throughout the year and therefore are characterised by a high PC1 (integrated NDVI, figure 2.17) and a low magnitude in PC2 (i.e. minimal seasonal variation). For both the South American and Asian continents TFs have been shown to have the greatest integrated NDVI (i.e. the area beneath the NDVI temporal curve) of all vegetation types. Townshend and Justice (1986) provide an analysis of the NDVI temporal profiles derived from the GVI data of Africa and the same authors in 1987 used NDVI profiles to produce a continental scale land-cover map for the whole of south America. Millington et al., (1989) used a similar technique for classifying the forests of Southern Africa. The assumption that similar integrated NDVI equates to a similar TF type or that a NDVI temporal curve equates to an identical biological vegetation phenology has not been rigorously tested however. The focus of all these investigations have been to reduce the effects of atmospheric perturbations and sensor-solar geometry variations. There are still anomalies in the methodology however. Townsend *et al.* (1987) report that very different TF types occasionally occupied the same position on their PC1 - PC2 feature space plot. Whilst, Zhu and Evans, (1994) (using 1km AVHRR LAC) report that spectral variations caused by physiographic factors, such as terrain changes, may result in spectral changes with amplitudes greater than any phenological changes.

Various attempts have been made to fit mathematical expressions to vegetation developmental curves using logistic or exponential expressions, Baret and Guyot (1991). Malingreau and Belward, (1992); Malingreau, *et al.*, (1996) use simple parameters linked to biological reality such as the onset of greenness, the peak of greenness and integrated NDVI.

So what has been the impact of these developments in algorithm design? In 1979, the FAO/UNEP initiated a project to update baseline information on the TFs of the world. This led to the widely-known Forest Resources Assessment (Malingreau et al., 1992). The exercise was recently repeated under the TREES project (JRC-ESA), initiated in 1990-91 (Singh, 1990). Almost all the efforts to map the extent and rates of deforestation have concentrated on mapping the forest/non-forest boundary (usually using LAC / HRPT AVHRR data) at both global (e.g. Nelson et al., 1987; Nelson and Horning 1993; Sader and Joyce, 1989) and regional (e.g. Nelson et al., 1986; Cross et al., 1991; Domelles and de Oliveira, ;1989; Nelson and Horning, 1993) scales. The TF biome is however far from uniform in composition, its ecological functions or its susceptibility to deforestation, Whitmore (1984a), and accurate mapping and monitoring of the TF ecosystem has not, to date, been performed routinely. Conservation biologists (e.g. Soule and Kohm, 1989) and ecologists (e.g. Lubchenco et al., 1991) stress the importance of biological diversity and acknowledge that remote sensing could be a valuable tool in mapping and monitoring the ecotonal variations of botanical lifesystems. This point is emphasised since gradients of seasonality are often evident between the evergreen and deciduous vegetation formations varying ecotonally. Further, the boundaries between cover types with similar phenologies such as those between moist savanna, TF and degraded TF are unreliable although some authors (Townshend and Justice, 1987) have suggested that on the south-eastern margins of the Amazon this boundary are particularly well defined by NDVI data. The use of the raster 'quantised' nature of remote sensing in monitoring the continuums of vegetation that make up the tropical biome, rather than the binary vector approaches detailed above, would prove a useful advance. Whitmore (1990) identified 15 TF types each of which he claims has a substantially different natural turnover,

deforestation (exploitation) rate, biodiversity potential and therefore potential for temporalspectral differentiation using earth observation data. Some attempts have been made to map different forest types of the TF biome e.g. Nitaya and Pala (1988); Achard and Blasco (1990), nevertheless research in this area needs to be extended (Stoms and Estes, 1993). Generally, little is known of the spatial variations in TF types and less still about the dynamics and seasonality of TF ecosystems.

So which satellite remote sensing systems are best suited to the task of monitoring of tropical forest phenology? Townsend and Justice (1988) divide the properties, of sensing systems, controlling the accuracy of phenological monitoring into three categories: (i) spatial, (ii) radiometric-spectral and (iii) temporal (see Figure 2.18).

- (i) Principal amongst the spatial properties, of sensing systems, important to spectral phenological monitoring, is the accurate registration of the image data time-series, since this factor alone will ultimately determine the accuracy of any monitored changes. Also of importance is the resolution of the sensing system (its IFOV) since this will determine the nature of the spectral changes detected and the degree of integration of the spectral signal (cf. section 2.5.3).
- (ii) The radiometric-spectral properties of the imaging system may be divided into two important groups. Firstly, the bandwidth, and location, of the channels. These will determine the types of biological changes that are detectable (cf. Section 2.5.1). Secondly, the radiometric calibration (both within and between image dates) will affect the accuracy of any spectral phenological changes detected.
- (iii) The temporal properties of the sensing system, i.e. the repeat cycle, which will ultimately determine the sampling frequency within which the investigation may take place.

# 2.9 SUMMARY

The task of monitoring the phenology, of TFs, using earth observing systems, is a difficult one. Complex integrations of the many land cover components, adjacency effects and atmospheric scattering all complicate the task of interpreting the seasonal reflectance changes and the relative contributions of substrate, canopy, sub-canopy and understorey strata (Figure 2.19). Changes in photosynthetic activity can and do occur at many different time scales (cf.

section 2.5.4, figure 2.11) and at many different spatial scales (cf. section 2.8.3). The AVHRR and the ATSR-2 have many of the spatial, radiometric-spectral and temporal qualities necessary to perform the task of phenological monitoring and represent the state-of-the-art in terms of large area land-cover analysis tools (Townshend *et al.*, 1991; Belward, 1991; Howard, 1991; Malingreau, 1991; Gond *et al.*, 1992). Ideally, a remotely sensed spectral phenology would result only from biological changes in vegetation. In reality however, variations in: illumination / view geometry; atmospheric optical depth; pixel size; as well as land-use changes result in potential differences between biological and spectral phenologies (Table 2.12).

Table 2.12 Sum	mary of the factors affecting spectral phenology
Factor	Effect on vegetation canopy reflectance
Biological changes	Ideally only these changes would cause variations in the satellite received reflectance.
Canopy cover, LAI & LAD	Increases and decreases in canopy LAI results in not only in the amount of photosynthetic changing but also variations in LAD and shadowing affects (Barret <i>et al.</i> , 1992; Colwell 1974; Strahler and Li, 1981; Horler and Ahern, 1986; Danson, 1987a; 1987b; Spanner <i>et al.</i> , 1990; Rosema <i>et al.</i> , 1992; Gerrard and North 1997). For example, specular reflectance will be greatest when the canopy is most dense (highest LAI), whilst LAI changes (from C to 8) may result in profound VI changes. This may pose serious problems in the differentiation of forests particularly those with more open stands (Peterson <i>et al.</i> , 1987).
Soil / Substrate / Understorey	The percentage of ground covered by vegetation affects the soil/substrate contribution to integrated reflectance. Where the canopy is discontinuous (even seasonally), the understorey or herb layer reflectance may become an important reflectance componen (Horler and Ahern, 1986; Peterson <i>et al.</i> , 1986; Rosema <i>et al.</i> , 1992; Gong <i>et al.</i> , 1993).
Size of the IFOV	Changes in the size of ground-area viewed (a function of off-nadir viewing) will affect both the amount received reflectance and the proportion of landcover units viewed.
Solar Elevation	Only small variations in solar zenith and azimuth positions affect tropical areas.
Sensor Elevation	Since TFs are not Lambertian reflectors, the zenith and azimuth position of the sensor wil affect recorded reflectance. This (view angle) will also determine the amount of soil/substrate visible to the sensor and the amount of shadowing. As the sensor moves away from nadir, less soil/substrate and more vegetation is recorded, typically causing a decrease in visible reflectance and an increase in near infrared reflectance (Curran, 1980; Barret <i>et al.</i> , 1992).
Atmospheric Effects	Cloud cover, atmospheric aerosols, water vapour, the proportion of direct and diffuse radiation may all affect the received reflectance signal. Their effects are complex and wavelength dependant (Barret <i>et al.</i> , 1992, cf. section 2.4.1). Further, TF areas are ofter affected by persistent cloud cover (Corves and Place, 1994)

In summary, the atmospherically resilient, GEMI, ARVI and NDVI are all known to be sensitive to soil (substrate) background variations, whilst SAVI and TSAVI are both effective in reducing the non-vegetation influences. Conversely, whilst many VIs show a similar response dependence to view angle variations, and a tendency to increase with increasing view zenith angle, the PVI and SAVI are generally very sensitive to changes in viewing geometry, whilst the ratio'ed indices (e.g. NDVI) are much less sensitive (Wardley, 1984).

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The choice of an appropriate vegetation index is then a difficult one, no one index being ideal for all sensors and / or vegetation formations. In general all VI models have been designed for specific (usually homogenous vegetation). Specifically there is a lack of indices designed for forestry applications, where factors such as shadowing and secondary scattering effects are important components of scene reflectance, and the vegetation heterogeneous. Peterson *et al.*, (1986); Townshend *et al.*, (1987) Lloyd (1988); Lloyd (1989c) all note the absence of a direct relationship between VI values and vegetation phenological changes (particularly in forests) and comment that is prudent to use a combination of different VIs. Huete *et al.*, (1994) pp. 233 conclude, in their review of indices for MODIS, '...that the basic framework of the NDVI can be maintained... with the addition of a soil correction term (L factor) and a blue band for atmospheric normalisation'. For this reason, three VIs will be used in this study, namely, the SAVI, NDVI and GEMI. This combination of diverse indices (after temporal compositing, radiometric and atmospheric correction) should prove adequate for the purposes of this investigation.

# CHAPTER 3 -MONITORING LARGE-AREA TROPICAL FOREST PHENOLOGY: I GROUND-BASED MONITORING

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# CHAPTER 3 -MONITORING LARGE-AREA TROPICAL FOREST PHENOLOGY: I -GROUND-BASED MONITORING

# 3.1 FIELD WORK AIMS AND OBJECTIVES

Although remotely sensed data may provide an unparalleled synoptic and temporal overview of phenology, the received reflectance signal is a spatial integration of many different biological phenological stages (cf. section 2.5.5). This has been defined as spectral phenology (section 1.2.1). Some of the information necessary for a detailed understanding, of biological phenological processes within TF ecosystems, may therefore be absent within spectral phenology. By monitoring both the individual biotic components (whose reflectance is detected by EO sensors in an integrated form) and the abiotic environmental stresses and triggers that drive the phenological processes, a comprehension of the relationships between biological phenology and spectral phenology can be attempted.

A field campaign along these lines was executed on a continuum of humid tropical ecosystems in eastern Bolivia. Monitoring commenced in the austral winter of 1995 and ran continuously for a duration of approximately 13 months, i.e. until the austral winter of 1996. The parameters monitored, and the data collection procedures used, were tailored specifically for the satellites used (ERS-2 ATSR-2 and NOAA-14 AVHRR). Special attention was paid to the provision of continuous, timely (with regard to satellite overpass times and illumination conditions) and compatible data (i.e. one that had a base sampling scale suitable for comparison with a 1km<sup>2</sup> remotely sensed dataset).

Within this, the first methodology chapter, the field sites and the data collection techniques are outlined (Table 3.1). For clarity of presentation the ground verification data has been divided into three sections. Section 3.1 introduces the field sites. Section 3.2 provides details of the methods used to inventory TF vegetation. Section 3.3 describes the monitoring of meteorological parameters using automatic weather stations. Section 3.4 describes the phenological monitoring of vegetative components using various techniques: litterfall monitoring (section 3.4.1); visual assessments of individual plant and community-level phenological stages (section 3.4.2); canopy monitoring using hemispherical photography (section 3.4.3); the monitoring of electromagnetic energy within the canopy using a hand-held Ceptometer (section 3.4.4) and the operation of an automated radiometry system (section 3.4.5).

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	Seasonal Semi-Deciduous Tropical Forest	Savanna Aborizada	Seasonally Inundated Humid Tropical Forest
Vegetation Inventory (Section 3.2)	✓	✓	~
Meteorological Observations (Section 3.3)	×	1	1
Litter Collection (Section 3.4.1)	✓	×	1
Visual Assessments (Section 3.4.2)	✓	✓	~
Observation of Canopy Dynamics (Section 3.4.3)	~	1	~
Ceptometry (Section 3.4.4)	✓	1	~
Automated Radiometry (Section 3.4.5)	~	1	1

Table 3.1 Monitoring techniques used at the field sites

# 3.1.1 Field Site Locations and Selection Procedures

The selection of field sites for this study was not undertaken on a purely scientific basis. Key logistical concerns of access, timing, safety, economics, practicality and academiccollaboration were all considered along with a strong scientific need to monitor representative tropical ecosystems. Three sites were selected, all of which represented 'natural' vegetation locations. All the field research presented here was undertaken in collaboration with Bolivian institutions (see acknowledgements for details).

A substantial climatic gradient (orientation north-west to south-east) exists across Amazonia particularly with respect to rainfall (Figure 2.1). Walsh (1996) describes the climates (and associated forest types) along this gradient as: a tropical Superwet climate, ameliorating progressively to become a tropical Wet / tropical Wet-Seasonal, and then a tropical Wet-Dry climate (cf. section 2.2.1). Eastern Bolivia is a microcosm of this gradient with most of the Amazonian climate types being represented. Regional meteorological phenomena, such as the *Surazo* (a cold wind which occasionally blows northward from the pampas during the austral winter), providing slight modifications to the general scheme. In lowland Bolivia, the wet season usually begins in October or November and ends by May. Some rainfall occurs during the dry season, but a moisture deficit usually occurs in the more

#### **CHAPTER 3, Ground Verification & Monitoring**

seasonal southern and easterly parts of the country between August and November. Three sites were monitored along this climatic gradient. In the following paragraphs (3.1.1.1-3.1.1.3) each site is introduced. Their locations can be found in Figure 3.1 and Map 1.

# 3.1.1.1 Lomerio (seasonal semi-deciduous tropical forest)

The Lomerio site lies in the Provinces of Nuflo de Chávez and Chiquitos in the Department of Santa Cruz. The region is characterised by a sub-humid climate with 3-5 dry months. Mean annual precipitation ranges between 1000-1500 mm and the mean annual temperature is 23° C. The area is part of the Brasilian shield, and contains characteristic undulating subdued ranges of hills (*Serranías*) punctuated by small igneous intrusions which form isolated outcrops (*Inselbergs*). These features generate a rolling topography with an altidudinal variation of 300 to 1200 m. Floristically the vegetation has affinities with both the central Amazonian (humid, evergreen) TF and the dry thorn forests of the Gran Chaco. The TF formation studied at Lomerio is part of a mosaic of TF vegetation types characteristic of the southern Brasilian Shield. The vegetation formations encountered at any location being a function of microclimatic factors and pedalogical conditions.

The forests at Lomerio are relatively undisturbed, although some selective logging has occurred. The monitored site is a BOLFOR (Bolivian forestry NGO) forest concession situated at  $-16^{\circ}$  31' 30'';  $-61^{\circ}$  50' 45'' with an average elevation of 400m a.s.l. (Figures 3.1 and 3.2). Within the concession, there are two large inselbergs and local relief variations of about 20 m are common. These depressions are seasonally inundated, creating zones with distinctive humic moisture regimes. The soils generally are relatively fertile being derived from metamorphic granitic rocks; red-yellow latosols being the most frequently encountered group (I.B.G.E., 1966).

# 3.1.1.2 Las Trancas (Savanna Aborizada)

The vegetation formations at Las Trancas ( $-16^{\circ}$  35' 35'';  $-61^{\circ}$  51' 48'') are situated on a dissected Tertiary planation surface, again on the Pre-Cambrian Brasilian Shield. The Las Trancas Savanna is generally well-drained, leading to the dominance of highly weathered and ferralitic red dystrophic ultisols and oxisols. The site is 14km southwest of the Lomerio site. *Cerrado* (savanna) vegetation, which is also known locally as *Pampa arbolada*, dominates the

area. This consists of grasses, occasional shrubs and frequent trees which usually occur in small clusters or islands. *Cerrado* vegetation in this area has been studied by Killeen *et al.*, (1990) and Killeen and Hinz (1990b) and is known to be floristically rich.

The climatic regime is very similar to that at Lomerio. However, the microclimatic conditions associated with savanna vegetation exaggerate the length and intensity of the dry season. Typically, this lasts from June until late August, at which time fires are common. These are frequently set at the end of the dry season to ensure good forage for the livestock of the area. These fires partially destroy the above-ground biomass to a height three to five metres. They result in a green flush with the increased humidity levels and first rains in October. The overall effect is to produce a sub-climax managed landscape-mosaic of savanna vegetation of different ages. Locational information can be found in Figure 3.2.



Plate 3.1 Savanna (foreground) and seasonal semi-deciduous forest (background), about 1km north of Lomerio

## **3.1.1.3** Chapare (seasonally-inundated tropical forest)

The third site is located in the Universidad Mayor de San Simon concessions at the Vallé del Sajta, Chapare, in the Department of Cochabamba (-17° 04' 15''; -64° 45' 49''), at an altitude of 212 m a.s.l. This protected area, which was established in 1973, encompasses approximately 6,000 ha of primary TF and a smaller area of 'managed' agro-forestry experiments.

Fluvial processes dominate this landscape resulting in an extremely dynamic vegetation mosaic developed on alluvial sediments. This contains large areas where, at the community level, there is no climax vegetation. The rapidly changing drainage pattern of shallow, widely-

spaced levees, broad depressions, and slowly in-filling ox-bow meanders leads to a great variety of environmental conditions.

Soils are alluvial, poorly-drained and characterised by a low pH (3-6). Fluvisols and Cambisols are the most frequent soil types. The climate is wetter and more humid than the conditions encountered at Lomerio and Las Trancas. It is characterised by a short drier period in July and August. The site is seasonally-inundated and therefore contains many successional stages characterised by relatively low species diversity. The prominent rectangular field (the location for one of the automatic weather stations, section 3.4, Plate 3.6; Figure 3.3) is aptly named Campo de Buffalo, since it contains South America's only herd of Indian Water Buffalo.



Plate 3.2 Seasonally-inundated humid tropical forest within the UMSS Concessions, Vallé del Sajta, Chapare

# 3.1.1.4 Summary

Three sites were selected for ground monitoring. Each was known to differ in:

- (i) its climatic seasonality; and
- (ii) the floristic and structural composition of its vegetation communities.

It was be expected therefore that both the spectral and biological phenologies would be markedly different at each site. The anticipated trend was that the drier vegetation formations of Lomerio and Las Trancas (3.1.1.1 and 3.1.1.2) would exhibit greater phenological seasonality than those at Chapare (3.1.1.3). The vegetation formations described in this section and the key environmental characteristics are compared in Table 3.2.

Table 3.2 A Comparison of the vegetation formations and key environmental characteristics of the field sites, after Killeen (1991); Killeen and Hinz (1992b); BOLFOR (1995c)

Vegetation	Main Soil Types	Typical Soil pH	Parent Material	Water Regime	Herbaceous Cover (%) & height (m)	Woody Cover (%) & height (m)	Fire frequency
Semi-	Ferrasols, Lixisols	6	Gneiss,	Well-	50-75%	>100%	Rare
Deciduous TF	& Nitosols	Ŭ	Schist	drained	(0.8)	(10-25)	Trate
Savanna	Dystric Ferrasols	5	Granitaid	Well-	100%	5-50%	Annual
Aborizada	& Nitosols	3	Granitolu	drained	(1)	(1-3m)	Aunual
Seasonally-	Fluvisols &	4	Alluvial	Periodic	50-75%	>100%	Novor
inundated TF	Cambosols	4	Anuvial	Inundation	(0.8)	(10-25)	INEVER

# **3.2 SAMPLING STRATEGY**

The spatial variation of biophysical parameters is usually continuous in natural landscapes. The creation and imposition of discrete verification areas is therefore rarely desirable. However, necessity dictates that some classification is usually necessary. For example, within this investigation, verification and monitoring is centred on three locations each hypothesised to exhibit a distinct phenological pattern. At Lomerio, the landscape is heterogeneous and delimiting the vegetation formations within a vector format is a highly subjective process (see Figure 3.2). Accurate ground data is required however for each TF formation to be verified, and this must be representative of both the dominant vegetation and any significant spatial variations present at each site. Similarly, the monitoring of change within each verification site must also embrace the diversity of cover types present.

Curran and Williamson (1985); Curran and Atkinson (1987); Atkinson (1987) and Congalton (1991) discuss the use of systematic and random sampling schemes in the context of remote sensing ground verification. They conclude that random sampling may underestimate small, but possibly significant, areas of variation unless the sample size is extremely large; whilst systematic sampling may under- or over-estimate important variations. For this reason, stratified random sampling is often used. These schemes usually rely on a prior knowledge of the spatial dependency of the variable of interest (e.g. leaf area, soil moisture).

The number of ground resolution cells that should be sampled for each verification site is a point for discussion. Dixon and Leach (1978) recommend a dataset of at least 30 ground cells, whilst Hay (1978) and Strahler (1980) suggest an accuracy assessment dataset of 50 ground cells. Bearing in mind these studies were based around the c. 78m<sup>2</sup> spatial resolution element of the Landsat MSS instrument, such high sampling rates seem reasonable. This study is however centred around the high temporal resolution of a 1km<sup>2</sup> data set and to survey large areas (of 30-50 km) would be logistically unrealistic. Further, it would not be desirable, for within the TF landscapes studied, the selection of more than a few 1 km<sup>2</sup> areas would result in the sampling of a different vegetation formations. Contamination may also result from neighbouring landscapes that have distinct and significant anthropogenic features. Therefore, what total area is it desirable to sample? The principal concern must be to maintain a large enough sample area to ensure that any analyses performed are statistically valid. Justice and Townshend (1981) address this issue, noting the importance of being able to locate verification sites within 1km<sup>2</sup> imagery. They proposed the following formula:

$$A = P(1+2L) \tag{3.1}$$

Where:

A is the minimum dimension of the sampling area (km) P is the dimension of the pixel (km)

L is the accuracy of location (number of pixels)

Solving [3.1] for 1 km<sup>2</sup> satellite imagery with an accuracy of +/- 1 pixel, each verification site needs to be represented by an area of at least 3 km<sup>2</sup> (3,000,000 m<sup>2</sup>) if the sites are in the nadir

portion of the image. Curran and Williamson (1985) propose a similar formula for calculating the area (per pixel) to be sampled. This incorporates the important factor of the spatial variability of the area;

$$A = \{D [G + (2 X)]\}^2$$
[3.2]

Where:

A is the area to be sampled,

D is the diameter of the ground resolution element (i.e. 1000m in the case of ATSR-2)

G the geometric accuracy of the imagery (assumed here to be +/- one pixel)

X is an arbitrary value a function of, landscape heterogeneity. In a very homogenous landscape e.g. an agricultural monoculture it is 0.5; in a heterogeneous landscape it can increase to 2.

Solving [3.2] for the two extremes of X:

$$A = \{1000[1+(2 * 0.5)]\}^{2}$$

$$A = 4,000,000 \text{ m}^{2}$$

$$A = \{1000[1+(2 * 2)]\}^{2}$$

$$A = 25,000,000 \text{ m}^{2}$$
[3.3]

Clearly a large area of forest, i.e. between 4,000,000  $m^2$  to 25,000,000  $m^2$ , must be surveyed and monitored in order to fulfil these criteria. However, monitoring more than a few ATSR-2 / AVHRR ground resolution elements may affect the definition of the respective TF forest classes.

In conclusion, an area of between 3 and  $6 \text{ km}^2$  is the optimal total sample size. This size reflects a compromise between the pressures of monitoring a statistically significant area, containing representative local variation, whilst still being representative of the vegetation formations.

# 3.2.1 Forest inventory

Within the context of this research, there is clear need for a contextual framework for the sampling and monitoring of phenological parameters. A forest inventory of each TF formation was therefore undertaken. This was achieved as follows.

- Clear objectives were defined concerning the information required from each inventory. Since vegetation inventories have financial and logistical constraints, recorded parameters were standardised so as to provide an estimate of each parameter at a known precision. The seven measurements taken during the inventories are outlined in Table 3.3 and have been described in section 2.2.2.2.
- 2. Sampling design. In the case of Lomerio a comprehensive inventory had been completed by the NGO managing the site. At the two other sites forest inventories were undertaken so as to be compatible with the Lomerio site (see 3.2.1.2 and 3.2.1.3, for details of their execution). The following field protocols evolved as 'good working practice' as a supplement to the techniques detailed in 2.2.2.2.
  - (i) The minimum height determination distance from observer to tree base was c. 1.5 times the apparent height of the tree.
  - (ii) That the vertical height measurement was estimated where ground level varies between the base of the tree and the observation point.
- (iii) That errors due to wind sway, average out, and therefore were discounted.
- (iv) The base of the canopy is defined as the lowest living (active) branch exiting the bole (above 1.3m).
- (v) That before dbh measurement commenced, all loose bark, lichen, ferns etc. were removed from the bole.
- (vi) The presence of commercially exploited species such as cacao trees were noted as they may be indicative of human disturbance.
- (vii) If the local mateiros (forest specialist workers) identification of species is in doubt, specimens of flowers and/or fruits and/or leaves were obtained and presented for identification at the herbarium in Cochabamba.
- (viii) During relascope surveys, special care was taken to view only a single tree not the combined silhouettes of more than one tree.

	Seasonal Semi-Deciduous Tropical Forest	Savanna Aborizada	Seasonally Inundated Humid Tropical Forest
Species	$\checkmark$	✓	✓
Total Height	✓	×	✓
Dbh (Diameter at Breast Height)	~	✓	✓
Height to Lowest Branch	$\checkmark$	×	✓
Crown Dimensions (Cardinal Points)	✓	×	1
Crown Shape (Geometrical Generalisations)	~	×	~
Relascope	×	✓	×

Table 3.3 Ecological inventory undertaken at the field sites

Total Height - Height to First Branch = Optical Depth ( $\tau$ ) of the canopy

Teams of three undertook the inventory work, one permanent record keeper and two people making measurements. Plots were permanently marked with plastic tags, trees with aluminium tree tags or paint. The x-y position of each tree was noted, referenced to the grid system and sample plot perimeters (BOLFOR, 1995b).

# 3.2.1.1 Methodology: seasonal semi-deciduous tropical forest

A quantitative ecological inventory had already been completed by BOLFOR for this site (BOLFOR, 1995). This was based on a multi-stage sample of the parameters listed in Table 3.3 undertaken as follows. All vegetation was recorded:

- (i) > 20 cm dbh (in two 20 by 10 metre quadrats per sector);
- (ii) 10cm to 20cm dbh (in two 10 by 10 metre quadrats per sector);
- (iii) 5cm to 10cm dbh (in two 10 by 10 metre quadrats per sector);
- (iv) height 1.3 m to 5cm dbh (in two 5 by 5 metre quadrats per sector);
- (v) height 30cm to 1.3 m (in two 2 by 2 metre quadrats per sector). See appendix 3.1.

These data were not available however during the fieldwork period, but became available later. The concession area (c. 5,000,000m<sup>2</sup>) had however been gridded and 100 sectors (each of 1ha) demarcated during the inventory (Figure 3.4). A topographical survey was also available.

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Plate 3.3 Lomerio, Access Road

The TF formation at Lomerio is of medium height and dominated by semi-deciduous trees, 12-25m (first branch 10-15m). About 140 species (dbh>20cms) are found at the site with an average of 24 tree species (120-140 individuals) > 20cm dbh per hectare. The most important tree families are the Leguminosae, Meliaceae, Bignoniaceae and Phytolaccaceae. The most common species being curupaū (*Anadenanthera macrocarpa*), jichituriqui amarillo (*Aspidosperma macrocarpon*), momoqui (*Caesalpinea puluviosa*), tasaá (*Poeppigia procera*) together representing almost a third of all trees > 20cms dbh. Amongst the emergents, the best represented individuals include roble (*Amburana cearensis*), cedro (*Cedrela fissilis*), cuchi (*Astronium urundeuva*) and soto (*Schinopsis x.*). Girth classes (dbh) reach a maximum of 1.3m. Architecturally this forest has two relatively simple strata. The top canopy is dense, but with many openings, and is dominated by trees with compound leaves. These have the ability to senesce rapidly when environmental conditions dictate (i.e. they are facultatively deciduous). The sub-canopy and understorey consist of trees < 10m, with both immature (developing canopy species) and sub-canopy specialists being represented. This stratum is also dense and irregular but characterised by more evergreen vegetation, commonly from the

families Leguminosae and Mimsoideae. On the forest floor one species in particular is notable, the garabatá (*Psuedoananas sagenarius*, Bromeliaceae) a succulent spiny fruit important in the local economy. Grasses are also common but seldom provide more than 5% of the total herbaceous cover, (Killeen *et al.*, 1990).

#### 3.2.1.2 Methodology: Savanna Aborizada

At this verification site, no vegetation inventory data was available. A relascope inventory was therefore undertaken. Four relascope 'sweeps' (c.  $40,000 \text{ m}^2$ ) were made using the methodology detailed in Appendix 3.2.

The term *cerrado* or Savanna Aborizada (wooded grassland) refers to a continuum of vegetation structural types. The woody flora of these areas is impressively diversified with over 400 woody species being represented (Sarmiento, 1983; Haase, 1990; Haase, 1989; Haase and Beck, 1989; Killeen, 1991; Killeen *et al.*, 1990). The most important tree families represented at this site are Vochysiaceae, Erythroxylaceae, Boraginaceae and Leguminosae. These range in height from 2m to 10m. Most species have large simple leaves with thick cuticles, e.g. *Curatella americana* and *Qualea grandiflora*. Herbaceous, sub-shrubby flora and perennial grasses dominate the landscape. The latter grow in characteristic tuffs which are approximately 10-30cm wide at ground level and form a discontinuous herbaceous stratum up to 1m in height during the rainy season (Plate 5.3). The total herbaceous cover ranges from 15 to 40 % and intricate vegetation mosaics of shrubs (*Davilla eliptica*), half-shrubs or half-woody species (e.g. *Pfaffia jubata*), grasses (e.g. *Mesosetum loliiforme*), sedges (e.g. *Cyperus flavus*) and semi-deciduous woodlands (cf. 3.2.1.1) are created (Sarmiento, 1983).

# 3.2.1.3 Methodology: (seasonally-inundated tropical forest)

Since no previous quantitative ecological inventories had been undertaken at this location, a Landsat-4 Thematic Mapper (TM) sub-scene (232\_072 {30-08-85}) was used to locate an appropriate area of the UMSS concessions. The area of spatial variation in vegetation was chosen (Figure 3.3) and three parallel 250 m transects were cut to traverse this zone. Included within the inventory area were levees, seasonally-inundated and *terra firme* zones. The variation in topography and therefore microhabitat, resulted in all common species being represented, (Israel Vargas, Museo Noel Kemph, Santa Cruz, *personal communication*, 1995).

Each transect was then divided into 0.2 ha plots which were demarcated using a calibrated cord. Each 250m transect contained therefore 20 plots (2 x 10 x 25m). All trees within each plot were examined, the attributes of Table 3.3 being measured, and tags attached. All trees  $\geq$  10 cm dbh were included in the inventory. All 20 plots were measured in Transect 1, i.e. a 100% inventory. In Transect 2, 10 plots were completed, i.e. a 50% inventory. Transect 3 was used for qualitative comparisons and sunfleck Ceptometer measurements only. Additionally two, randomly located, 5 x 5 m sub-plots, were inventoried to provide information on <u>all</u> vegetation present (i.e. trees < 10 cm dbh, shrubs and herbs).

The forests of the UMSS concessions are best described as a mosaic of successional continuums with elements of the tropical wet forest and premontane wet forest life zones of Holdridge *et al.* (1971) being represented. Past and recent inundation events have resulted in a tall, multi-layered dense canopy punctuated by emergent trees of 25-30m in height. The canopy is diverse in composition but has no true dominants. Prominent species include the palms: e.g. *Astrocaryum murumuru* and *Iriartea venricosa*; figs: e.g. *Ficus insipida, Socratea exorhiza* and *Calycophyllum spruceanum*. Many of these trees have specialist adaptations, e.g. plank buttresses or respiratory aerial root systems, that help cope with inundation episodes. Trees present are mainly evergreen with the occasional deciduous tree from the vegetation formations of the semi-deciduous Brasilian shield (see 3.2.1.1 above). The understorey vegetation is abundant, dense and typically contains foliage from 1.5-17 m high. Prominent families here include Rubiaceae, Gesneriacae, Begoniacae and Zingereraceae. Vascular epiphytes (ferns and orchids) are common at all heights.

# 3.2.1.4 Summary

- 1. A forest inventory was conducted at each ground monitoring site to verify the type of vegetation community present.
- 2. The locations for the monitoring and observation of biological phenology could now be set within a framework that embraced the heterogeneity of each site, i.e. by sampling as diverse a range of microclimatic environments as possible.

The total area surveyed at each site is shown in Table 3.4.

Location	Area of Forest Inventory (m <sup>2</sup> )		
Lomerio	20,000		
Las Trancas	40,000		
Chapare	15,000		

Table 3.4 Total area of forest inventory at the three field verification sites

# **3.3 OBSERVATIONS OF METEOROLOGICAL PARAMETERS**

Almost all tropical environments experience seasonal variations in temperature, humidity, rainfall, evaporation and wind speed. All of these factors may then potentially play a role in triggering phenological changes in tropical vegetation (cf. section 2.3). Monitoring these meteorological variables in a timely and accurate manner is then critical to this study. Ideally, each tropical forest site would have its own micro-meteorological monitoring apparatus mounted *in situ* within the vegetation. Such a methodology has its problems however since such measurements: are difficult to achieve with finesse (cf. section 2.7.2); and would not be representative at a spatial scale general enough to be applicable to the whole vegetation formation.

Two general-purpose NERC Automatic Weather Stations (AWS) were available for this research and were installed at Las Trancas and Chapare ground-monitoring sites. For the AWS technical specifications see Appendix 3.3. At each site the following parameters were recorded.

- (i) <u>Net radiation</u> (here the difference between the incoming and outgoing components of radiation fluxes) was measured using a net radiometer. This consists of a flat black plate exposed to both downward-welling and upward-welling EMR. The temperature difference developed between the top and bottom surfaces is assumed proportional to net irradiance. To overcome the effect of wind, the Plate is protected by a polythene (Funk) envelope which is transparent to EMR between 0.3 and 14 μm. Instrument performance may be affected by rain and dust accumulation. Cleaning of the sensing surfaces and replacement of contaminated envelopes was, therefore, undertaken each time the station was visited.
- (ii) <u>Total solar radiation</u> (the sum of direct and diffuse radiation) was measured by a solarimeter. This consists of a thermopile protected by a glass hemisphere which is opaque optically to all directional and spectral EMR between 0.3 and 30  $\mu$ m (Gates, 1962). Instrument performance may have been affected by occasional condensation inside the dome, however no remedial action was possible. Sellers *et al.* (1989) working with AWS from the same instrument pool, in a similar environment, calculated systematic errors in the solar and net radiation to be around 5 percent or 5 W m<sup>-2</sup>.
- (iii) <u>Air temperature</u> was measured with a thermometer. In order to measure temperature accurately, all forms of heat exchange between the sensor and its environment (other

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than convection) must be minimised. Radiative errors were reduced by surrounding the thermometers with a shield of twin concentric aluminium cylinders which maintained temperature close to that of the environment (Szeicz, 1975).

- (iv) Wet bulb depression was measured using a psychrometer. Two thermometers of identical shape and size were deployed to measure air temperature (dry bulb) and wet bulb temperature. The latter was achieved by covering the second thermometer with a sleeve of wet muslin, thereby subjecting it to evaporative cooling. In the absence of an external energy source, all of the energy used to evaporate water is supplied by the surrounding air (Jones, 1993). The reservoir irrigating the muslin required frequent replenishment. Occasionally (in times of high evaporation) inspection revealed that no water was present, invalidating the wet-bulb depression and therefore the humidity and evaporation measurements. Sellers *et al.*, (1989) estimates errors of air temperature and wet bulb depression to be 0.25°C or 10 %, whichever is the greater.
- (v) <u>Wind speed</u> was measured using a cup anemometer. This consists of three hemispherical cups mounted on arms and attached to a central vertical spindle which is free to rotate in the wind. Monitored rotation is assumed directly proportional to wind speed. Because of internal friction, cup anemometers have a finite stopping speed (between 5 and 20 cm<sup>-1</sup>). Above this stopping speed response is almost linear (Jones, 1993). These instruments also require a minimum fetch (unobstructed horizontal flow) which is typically 100 to 200 times the height of the nearest tree.
- (vi) <u>Wind direction</u> was measured using a wind vane. This traditional instrument consists of an arm fitted with a sail. The arm position will always be parallel to the wind direction. These directional measurements are prone to systematic error of up to +/- 20 degrees, and suffer from stalling errors (below 0.5ms<sup>-1</sup>) similar to those of the cup anemometer.
- (vii) <u>Precipitation</u> was measured using a tilting-bucket rain gauge. This instrument measures the amount of rain per unit area falling into an orifice. Errors include wetting (where precipitation is insufficient to tilt the bucket and subsequently evaporates), splash and wind blow errors. The sum of all of these are estimated to be +/- 5-10%, (Szeicz, 1975).

	Lomerio	Las Trancas	Chapare
Net Radiation	×	✓	$\checkmark$
Total Radiation	×	✓	✓
Air Temperature	×	✓	✓
Wet Bulb Depression	×	✓	✓
Wind Speed	×	✓	✓
Wind Direction	×	✓	✓
Precipitation	×	✓	✓

Table 3.5 Meteorological measurements at the field sites

 $\checkmark$  = measurements representative of the field verification site

★ = no measurements at the field verification site, but the Las Trancas measurements used (14 km away)

Using the above seven directly monitored meteorological measurements two further parameters were derived.

(i) <u>Relative humidity</u> this was calculated by noting the depression of the wet bulb temperature relative to the dry bulb temperature:

$$e = e_s T_{WET} - \Upsilon(T_{DRY} - T_{WET})$$
[3.4]

where:

 $T_{DRY}$  and  $T_{WET}$  are the dry and wet bulb temperatures,

 $e_s T_{WET}$  is the saturation vapour pressure at the wet bulb

(which is temperature dependant and is derived from look-up tables), and,

- $\Upsilon$  is the psychrometric constant (equal to 66 Pa ° C<sup>-1</sup>) at sea level in a ventilated psychrometer, (Jones, 1992).
- (ii) <u>Potential evaporation</u> (cf. section 2.3.2) was calculated using the Penman equation (an estimation of evaporation from a free water surface). The AWS automatically calculates the potential evaporation using the temperature difference between the dry and wet bulbs and terms derived from net radiation, wind-speed and station altitude (air pressure). See Appendix 3.4 for details.

# 3.3.1 Installation of the Automatic Weather Stations

Installation sites were chosen for the AWS according to the following criteria:

- (i) that the ground should be level;
- (ii) the area should have sufficient fetch to validate wind run and direction monitoring; and

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(iii) the area should not be prone to inundation.

All instruments were positioned so as their supports and cables did not interfere with measurements.

#### 3.3.1.1 Las Trancas

The first AWS was installed at the community of Las Trancas on the 21 July 1995. It was placed in the compound of an elder of the community (Casa del Felix) for security. The transient nature of local employment in this area meant, however, that his family were rarely present. No problems were encountered at this site.



Plate 3.5 AWS at Las Trancas

# 3.3.1.2 Chapare

Under local advice this AWS was installed on 10 September 1995 in an area of dry ground in the middle of the verification area (see Figure 3.3). This necessitated transporting the AWS down the Rio Isarma and then carrying the instruments 8 km from the boat demarcation point through the forest to higher land used for grazing buffalo. This effort was justified since the rest of the site is prone to annual flooding in January and February. Further problems arose when some of the buffalo developed an affinity for the AWS. The University Mayor de San Simon erected a fence (see Plate 3.6) in December 1995 to prevent further buffalo encroachment. CHAPTER 3, Ground Verification & Monitoring



Plate 3.6 AWS at Chapare

# 3.3.1.3 Maintenance

Due to the sometimes extreme conditions that the AWS had to operate in, instruments were serviced frequently, glass covers cleaned, electrical components checked, sensitive surfaces re-levelled and orientations confirmed. However, major problems did occur with the Chapare AWS. Power cables were severed on several occasions by rodents chewing through the solar panel-battery line. This resulted in the system losing power, the batteries draining and the logger to cease recording. Lack of local replacements led to motorcycle batteries being used as replacements, nonetheless some data were lost.

# 3.4 PHENOLOGICAL MONITORING

In this section, a methodology for monitoring the progression of TF vegetation components through their seasonal phenological phases is presented. This is achieved through a combination of direct qualitative methods (e.g. visual assessment) and quantitative indirect techniques (e.g. monitoring vegetation reflectance changes with purpose-built radiometers).

The first technique presented (section 3.4.1) involves the monitoring of phenology using measurements of litterfall, i.e. the component parts of vegetation that fall to the ground. The second approach (section 3.4.2), visual assessment of phenological condition, was attempted at the individual plant scale as well as stratum-wide. The third technique (section 3.4.3) monitored canopy dynamics using hemispherical photography. The fourth technique quantifies changes in the LAI of the canopy (section 3.4.4) whilst the last section monitors reflectance at various heights within the canopy (section 3.4.5).

# 3.4.1 Monitoring litterfall

Litterfall was collected each month between July 1995 and November 1996. Initially, all three sites were monitored, although logistical difficulties led to the abandonment of litterfall monitoring at one site (Las Trancas). Monitoring was achieved using two techniques:

- (i) a litter-trap (mesh basket) method for monitoring fine litter; and
- (ii) small clearings (2m<sup>2</sup>), on the ground, to observe branch and other large litter components as well as fine litter fall.

	Seasonal Semi-Deciduous Tropical Forest	Savanna Aborizada	Seasonally Inundated Humid Tropical Forest
Fine Litterfall (Leaves, Twigs, Flowers, Fruit & Frass)	~	×	×
Total Litterfall	✓	*	✓
$\checkmark$ = measurements made	<u> </u>	······································	

Table 3.6 Litterfall Monitoring at the Field Sites

 $\mathbf{x}$  = no measurements made
### 3.4.1.1 Experimental design

Initially, 2 m x 2 m square traps were constructed from wood and plastic mesh. This mesh had a perforation aperture of 2.5 mm. The positioning and maintenance of these large and cumbersome traps caused excessive vegetation disturbance. This combined with the rather



Plate 3.7 A Litter Collecting Basket at Lomerio

coarse mesh aperture, led to the replacement of these traps with smaller circular models. These were constructed from 3 mm wire, deformed into a circle 40 cm in radius thereby producing an area of  $0.5 \text{ m}^2$ . Agricultural plastic netting was obtained locally and then sewn with fishing line to form a basket (Plate 3.7). The mesh perforation aperture of the circular traps was 0.5mm and therefore a far greater amount of fine litter was collected. A rock was placed in the bottom of each trap to prevent the basket contents from being emptied by the wind. Baskets were placed 1m above the ground to

reduce excessive litter decomposition between fall and collection. Parker *et al.* (1989) and Proctor (1987) indicate that losses through decomposition in a six week period (the maximum between-collection period in this study) may be up to 50% of dry weight if the sample is in contact with the soil. Such errors are to some degree standardised however, since the sampling time-interval was relatively constant and the microclimate varied little between traps at each site. Other errors include leaf consumption by insects, this can be estimated using the frass fall sub-sample (Adis *et al.*, 1979).

Total litterfall was measured using 2 m by 2 m ground plots, as recommended by Gosz *et al.*, (1972). Each plot was cleared of twigs, branches and all vegetation at the beginning of the study. Branches and litter which had fallen in the clearing were then collected monthly. The clearing was then swept clean for the next months litterfall.

### 3.4.1.2 Seasonal semi-deciduous tropical forest

Initially, four square litter traps were installed at Lomerio in July 1995. In September 1995 these baskets were replaced with 12 circular  $(0.5m^2)$  litter baskets. In addition, four clearings were prepared. The positions of these baskets and cleared-plots were randomly determined within the concessions. The forest at this verification site was therefore represented by an area of  $6m^2$  (12 traps) to measure fine litterfall, and  $22m^2$  (4 plot-clearings and the 12 traps) to measure total litterfall. Litterfall was recovered monthly at each location. Litter collected was then placed in polyethylene sample bags and the details recorded. Occasionally, due to problems of access, this monthly collection cycle had to be varied by +/- 5-10 days. Because of this, and the unequal length of calendar months, all measurements were standardised by dividing the sample weights by the number of days the traps collected litter. This provided a daily measurement which may then be composited into time periods of an useful length e.g. weeks, months etc.

Saito and Shidei (1972) note that differences in leaf fall recorded between square, circular and triangular litter traps are minimal. More importantly, they conclude that the minimum size (or diameter in the case of a circular trap) of a litter basket should be one whose length is twice the maximum length of leaves to be caught. Since both the square and circular baskets conform to this rule results obtained using the two basket configurations are comparable.

### 3.4.1.3 Savanna Aborizada

Litter traps, of the original square variety, were installed at Las Trancas. The close proximity to the community of Las Trancas and the usefulness of the 2.5 mm netting meant that in spite of donating spare mesh to the community, these traps frequently had disappeared when I went to collect the litter. Therefore, litterfall monitoring at this site was abandoned in November 1995. No clearings were created at this site, since; the high density of cattle would have caused constant disturbance.

### 3.4.1.4 Seasonally-inundated tropical forest

The methodology for measuring both fine and large litterfall at Chapare was similar to that for Lomerio (section 3.4.1.2). The traps and clearings were randomly located within the forest

inventory area. The entire site was therefore represented by an area of 22 m<sup>2</sup> (12 traps and four clearings) to collect total litterfall and 6 m<sup>2</sup> (12 traps) to measure fine-litterfall.

### 3.4.1.5 Maintenance of apparatus

The major unforeseen advantage of changing the litter trap design was the ability to repair and replace the traps as and when necessary. It served to illustrate that the use of locally available materials should be employed wherever possible. On numerous occasions, minor repairs were necessary. Even when emergency repair supplies ran low, a short trip of only two days, was all that was necessary to purchase materials and effect repairs. Finding imported components would have necessitated visiting a large city and incurred a minimum delay of about a week.

### 3.4.1.6 Post-collection procedures

As noted previously, the litter samples were placed into polyethylene sample bags. This procedure, whilst keeping the sample isolated and clean, also traps any water (and water vapour). In the tropics such closed, high humidity conditions may lead to rapid sample decomposition. Great care was taken therefore to minimise the period between sample collection and initial drying. This was undertaken in a domestic oven, at a temperature of c. 70 ° C, for a period of not less than two hours. Each sample was then weighed and split into two. The two sub samples were then weighed. One sub samples were then re-dried, in a laboratory drying oven to constant weight at 105 ° C. Each sub sample was then separated into vegetative components. Leaves were sorted first. The non-leaf litter was then sorted into: wood (twigs and branches), fruits, flowers, epiphytes, and frass. The dry weight was then determined for all these component part, trap and date (Gosz *et al.*, 1972; Adis *et al.*, 1979; Parker *et al.*, 1989).

Leaf area lost through litterfall will profoundly effect vegetation reflectance through changes in LAI. For this reason, a quantification of the leaf area lost during each month is desirable. A double sampling technique was therefore employed whereby a 10% sub-sample of the leaf litter population was taken, and used to calculate leaf area directly. A linear regression ratio between this leaf area and the weight of the sample was then used to infer the leaf area index of the whole leaf litter sample.

### 3.4.2 Visual assessment of phenological condition

Since this aspect of the research sought to understand TF phenology at the community level, numerous quantitative measurements are desirable. Initially, leaf tagging experiments were attempted to monitor leaf burst and expansion on a monthly basis for a number of individual trees. The length and width of selected leaves were measured to the nearest 0.1 cm (Ralhan and Singh, 1987) and leaf area calculated as 2/3 lamina length (to the base of the tip) x breadth (Cain *et al.*, 1956; Njoku, 1963; Norman and Campbell, 1989). Paint, sticky-tape, staples, glue and epoxy resins were all applied to leaves and stems, but no satisfactory method could be found to measure flushing and expansion on a monthly basis. These measurements were therefore abandoned in favour of qualitative visual assessments of leaf status on a four point scale (absent, emerging, expanded and senescing). This standardisation allowed comparison between verification sites and minimised subjective factors. Assessments were made on:

- (i) the ground and sub-canopy stratum; and
- (ii) on randomly selected individual plants.

The use of leaf texture and colour as indicators of age was not attempted as such methods have been discredited (Lieberman, 1982). Flowering was measured as a binary (presence or absence) observation. All bud types from just opening to senescing flowers were counted under one category (presence). A presence or absence system was also used for fruiting. All fruits whether immature or mature were included under one category (presence). This methodology was flexible enough to allow for the detection and allocation of more than one phenophase in a stratum or a single tree (Waggoner, 1974).

### 3.4.2.1 Observation procedures

The phenological stage of the sub-canopy and ground vegetation was assessed on a monthly basis, at the same time litter was collected. The phenological condition of randomly selected individual plants (at least two from each strata) were also noted. Photographic records were kept to aid in these assessments. An example of a field monitoring sheet is shown in Appendix 3.5.

### 3.4.2.2 Seasonal semi-deciduous tropical forest

Observations commenced in September 1995 and continued until June 1996. The details are shown in Table 3.7.

Table 3.7 visual assessments of phenole	gical conunion at Lonierio		Contraction in the
Visual Assessment Strata Observations	Leaf Status Absence (1) Emergence (2) Fully Expanded (3) Senescence (4)	Flowering (Presence ✓) (Absenence ≭)	Fruiting (Presence ✓) (Absenence ≭)
Sub-Canopy	(1/2/3/4)	√/x	√/x
Ground	(1/2/3/4)	√/x	√/x
	Contraction of the second	the second second	
Visual Assessment Specific Point Location Number Botanical Name	Leaf Status	Flowering	Fruiting
<b>Ground 1</b> Garabatá ( <i>Pseudoannanas sagenarius</i> ) Bromeliaceae	(1 / 2 / 3 /4)	√ / x	√/x
<b>Ground 2</b> Sirarí ( <i>Peltogyne sp.</i> ) Caesalpinoideae	(1 / 2 / 3 /4)	√ / x	√ / x
<b>Ground 3</b> Immature Soto <i>(Schinopsis cf. brasiliensis)</i> Anacardiaceae	(1 / 2 / 3 /4)	√ / x	√ / x
Canopy 1 Curupaú (Anadenanthera macrocarpa) Mimosoideae	(1 / 2 / 3 /4)	√ / x	√ / x
Canopy 2 Momoqui ( <i>Caesalpinea puluviosa / floribunda</i> ) Caesalpinoideae	(1 / 2 / 3 /4)	√ / x	√ / x

Table 3.7 Visua	l assessments of	phenological	condition at	Lomerio
1 4010 J./ VISUC	i assessments or	DIRTICIOEICAI	condition at	LUIIUIU

Two canopy trees (a Curupaú, *Anadenanthera macrocarpa* and a Momoqui, *Caesalpinea puluviosa or c. floribunda*) and three smaller ground-stratum trees (Garabatá, *Pseudoannanas sagenarius*; Sirarí, *Peltogyne sp.* and an immature Soto, *Schinopsis cf. brasiliensis*) were observed for changes in their leaf status, flowering and fruiting. The Sirarí and Curupaú trees were destroyed between February and March 1995, and the Soto between March and April 1995 by the experimental logging that was ongoing in the BOLFOR concessions. Sub-canopy observations were unaffected by the loss of these observation trees.

# 3.4.2.3 Savanna Aborizada

Observations commenced in September of 1995 and continued until June 1996. The details are shown in Table 3.8.

Visual Assessment Strata Observations	Leaf Status Absence (1) Emergence (2) Fully Expanded (3) Senescence (4)	Flowering (Presence ✓) (Absenence ≭)	Fruiting (Presence ✓) (Absenence ≭)
Ground	(1/2/3/4)	√/x	√/x
Trees	(1 / 2 / 3 /4)	√/x	√/x
Visual Assessment Specific Point Location Number Botanical Name	Leaf Status	Flowering	Fruiting
<b>Grass</b> (Mesosetum loliiforme)	(1 / 2 / 3 /4)	√/x	√ / x
<b>Tree 1</b> Trampillo ( <i>Lafoensia pacari</i> ) Lecythidaceae	(1 / 2 / 3 /4)	√ / x	√ / x
<b>Tree 2</b> (Qualea grandiflora) Vochysiaceae	(1 / 2 / 3 /4)	√ / x	√ / x

Two trees, a trampillo (*Lafoensia pacari*) on an inselberg and a *Qualea grandiflora* in the savanna grassland were observed at Las Trancas. Tussocks of the grass the *Mesosetum loliiforme* adjacent to the ARS monitoring experiment (see section 3.5) were also assessed.

### 3.4.2.4 Seasonally-inundated tropical forest

Observations commenced in September 1995 and continued until June 1996. The details are shown in Table 3.9.

Table 3.9 Visual Assessments of Phenological Condition at Chapare

Visual Assessment Strata Observations	Leaf Status Absence (1) Emergence (2) Fully Expanded (3) Senescence (4)	Flowering (Presence ✓) (Absenence ≭)	Fruiting (Presence ✓) (Absenence ≭)
Sub-Canopy	(1 / 2 / 3 /4)	√ / x	√ / x
Ground	(1 / 2 / 3 /4)	√ / x	√ / x
Visual Assessment Specific Point Location Number Botanical Name	Leaf Status	Flowering	Fruiting
Ground 1 (Mara Marcho)	(1 / 2 / 3 /4)	√ / x	√ / x
<b>Ground 2</b> (Gesneriacae)	(1 / 2 / 3 /4)	√ / x	√ / x
Sub-Canopy 1 Pachiuva ( <i>Iriartea venricosa</i> ) Palmae	(1 / 2 / 3 /4)	√ / x	√ / x
<b>Canopy 2</b> Charque ( <i>Eschweilera coriacea</i> ) Lecythidaceae	(1 / 2 / 3 /4)	√ / x	√ / x

## 3.4.3 Monitoring canopy dynamics using hemispherical photography

Any description of canopy state or condition is highly subjective without some form of graphical aid. Inventory profile diagrams, statistics of height, dbh, bole density or visual assessments provide useful starting points. However, these methods lack a quantification of canopy dynamics. Black and white hemispherical photographs have been successfully used to characterise forest canopies (Evans, 1956; Evans and Coombe, 1959; Evans, *et al.*, 1960; Grubb *et al.*, 1963; Anderson, 1964a; 1964b; 1964c; Grubb and Whitmore, 1966b; Bjorkman and Ludlow, 1972a; Rich, 1990; Chen *et al.*, 1991; Mitchell and Whitmore, 1993) (cf. section 2.7.2). The area and number of canopy 'gaps' being indicative of light penetration and canopy openness. Since this research requires a quantification of canopy dynamics to verify remotely sensed data, black and white photographic measurements, taken under the canopy, should ideally:

- (i) be repeatable at the same location so that a standardised estimate of the same area the sky : canopy can be monitored; and
- (ii) have similar illumination conditions (diffuse:direct EMR ratio) to the remotely-sensed data.

Although some authors (e.g. Barrie *et al.*, 1990) recommend the acquisition of hemispherical photographs in overcast conditions (at low sun-elevations or even the blocking of any direct sunlight using a card) to allow strata to be differentiated, standardisation with image acquisition time is probably more useful since this will ensure the same canopy illumination conditions (optical depth) at each acquisition date.

A Minolta 7000 camera fitted with a 28mm f 2.8 lens was used to acquire the hemispherical photographs. This was mounted on a monopod, extended to a height of 1.7m (the most comfortable operating height). Since the horizon was rarely visible, manual levelling to the horizontal was achieved using a spirit gauge. Evans and Coombe (1959) claim this method may achieve an accuracy of up to  $\frac{1}{4}$  of a degree (i.e. equivalent to 1 solar minute). The camera top was orientated to geographic south. The automatic exposure facility was used, with the proviso that the shutter-speed should exceed  $1/125^{\text{th}}$  of a second to avoid blurring of the photo. The use of the automatic exposure facility caused some problems since the camera light meter has a centred weighted bias of  $+/-45^{\circ}$  of nadir. Experiments by Unwin (1980) derived the following equation:

$$I = \frac{244}{F} \frac{n^2}{t}$$
[3.5]

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where:

*I* is the illuminance;

*F* is the ASA rating of the film;

*n* is the lens aperture (f number); and

t is the exposure time in seconds.

Average exposure indicated by the camera light meter was found to be of the order of 1-4 stops smaller than that calculated from photometer readings. All hemispherical exposures were therefore replicated with the f-stop increased by a factor of 2. Kodak T-Max professional black and white film (ASA100) was used throughout this study. All hemispherical photographs were acquired between 10:15 and 15:15 local solar time. Experimental transects of hemispherical photographs were taken using a similar method to that outlined by Nilson and Peterson (1991). This has the advantage of accounting for the high variability of structure in the TF verification sites.

Four points were located randomly within the Lomerio and Chapare sample areas and monitored monthly between July / August 1995 until June 1996. The standardised acquisition height of 1.7 m was relaxed at Las Trancas site since the reduced height of the vegetation necessitated a lower monopod height (Plate 3.8). There only one point was monitored from July 1995 until June 1996.



Plate 3.8 Hemispherical Photograph Acquisition at the Savanna Aborizada Site - 91 -

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### 3.4.4 Monitoring canopy dynamics using a Sunfleck PAR Ceptometer

Several predictable relationships exist between canopy LAI and the amount and spatial distribution direct and diffuse radiation fluxes (Canham, 1988; Campbell and Norman, 1988). These fall into two broad categories. Those based on the spatial distribution of sunflecks (direct solar radiation that has passed through the canopy unattenuated); and those based on the proportion of PAR absorbed by the canopy. The Sunfleck Ceptometer is an instrument than measures both these parameters simultaneously. Sunfleck and/or PAR measurements may then be inverted (using appropriate radiative transfer models) to retrieve estimates of LAI. The accuracy of these estimates depends on several conditions, most notably adequate spatial sampling beneath the canopy; and the radiation model used in inverting the data.

The most appropriate sensor length (i.e. the number of horizontal sampling points beneath the canopy) depends on the average plant or leaf spacing and height. For example, in a dense canopy of fine-leafed grass a length of 1m is more than adequate (Decagon, 1995). In a citrus plantation with three metre bole spacing a 1 m long sensor would be to short. In the context of a TF, a transect of readings is more appropriate (in order to simulate a very long sensor length). When such transects are walked on a regular basis, changes in canopy gap-fraction and LAI over time can be assessed and monitored.

Several different canopy radiation models are available to invert Ceptometer data (Decagon, 1985). Selection of an appropriate model to suit the canopy characteristics is especially important (see section 5.2.4).

#### 3.4.4.1 Operation and Measurement

The Sunfleck Ceptometer is a hand held array of photo-diodes sensitive to PAR (EMR from 0.4 to 0.7  $\mu$ m) (Plate 3.9). Eighty diodes are presented in a linear array at 1cm intervals, each discretely measuring received radiance. The array must be kept horizontal during measurement. Operations commenced with the acquisition of a fully sunlit reading (usually in a nearby large clearing). A sunfleck threshold was then defined at 50% of this amount. Measurements were undertaken along 250m transects every 10m. A sunfleck is detected when the (full sunlight) threshold reading is exceeded by one or more of the diodes. These sunfleck measurements can only be acquired on clear days at high solar elevations (i.e. between 10:00 - 15:00). This is since the solar body must approximate a point source in order to cast shadows.

PAR attenuation measurements may be recorded under all sky conditions from cloudless to cloud-free.

Two transects were walked monthly at the semi-deciduous forest site, from July 1995 until June 1996. These traversed many of the concession's micro-topographical features and their associated micro-climatic environments (Figures 3.2 and 3.5).

Measurements at the seasonally-inundated TF (Chapare) were undertaken monthly along the three base-line ecological inventory transects (machete trails) from August 1995 until June 1996. These are parallel to each other and traverse the gradient of maximum (topographic and successional) variation (Figure 3.3). No Ceptometer measurements were taken at Las Trancas.



Plate 3.9 Ecological Inventory Baseline at the Seasonally-inundated Tropical Forest, Ceptometer in Foreground

# 3.4.5 MONITORING THE REFLECTANCE DYNAMICS OF GROUND, UNDERSTOREY AND TREE STRATA USING AN AUTOMATED RADIOMETRY SYSTEM

The review of radiometry (cf. section 2.7.3) outlined the following criteria for an automated radiometry system (ARS) in a tropical forest. It should:

- (i) simulate the wavelengths and band-pass widths of the satellite sensors used in the study;
- (ii) monitor reflectance and irradiance synchronous with the satellite overpasses;
- (iii) be easy to install and maintain, and ideally be user-designed (Bingham and Long, 1993);
- (iv) be robust and environment proof (Szeicz, 1975; Szeicz, 1968); and
- (v) sample numerous points simultaneously to facilitate an understanding of the variations in reflectance-components which are integrated at a 1 km scale, and minimise errors introduced by rapid variations in illumination (Evans, 1956).

### 3.4.5.1 Design and Construction

Since no commercially available equipment met all the above criteria, an ARS was designed and constructed. The first task was to simulate the ATSR-2 and AVHRR spectral ranges and bandwidths. Ideally, these would be identical to those of the satellite instruments in terms of the photo-sensitive compounds and spectral filters (defraction-gratings) used. Enquiries were made at the Rutherford Appleton Laboratories (the builders of ATSR-2) to obtain the '*test-generation*' detector arrays. Although this idea was enthusiastically received, lack of action and time constraints led to the use of off-the-shelf (industry standard electronics components) photo-sensitive compounds and spectral filters. In hindsight, the lack of the exact satellite-replica photo-diodes simplified instrument construction enormously.

The only commercially available composites suitable for long-term field experiments are silicon- or gallium-arsenide-phosphide-based. These operate efficiently at terrestrial temperatures (requiring no cooling) and are extremely small in size and weight. Their deployment throughout TF structures can therefore be achieved without substantial alteration to the bi-directional illumination and reflectance fields (i.e. with finesse). In contrast, a mercury-cadmium-tellurite composite (a military-restricted product, commonly used in earth

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observing sensors, that requires cooling by liquid nitrogen) would have made a very accurate but extremely cumbersome and expensive field instrument.

The next problem was that of limiting the spectral response spectra of the silicon photodiodes (Figure 3.6) to one that approximated the bandwidths of the satellite instruments (Table 3.10).

Table 3.10 Comparison of the Band-Pass Widths of NOAA-14 AVHRR & ERS-2 ATSR-2

AVHRR	ATSR-2	
0.58-0.68 μm	0.545-0.565 μm	
0.735-1.1 μm	0.649-0.669 μm	
3.55-3.93 μm	0.855-0.875 μm	
10.3-11.3 μm	1.58-1.64 μm	

Again, the use of the actual defraction gratings from the respective satellite-sensors would have been the ideal solution. Indeed, the only way to accurately simulate the very narrow band-pass widths of the ATSR-2 sensor (cf. section 2.8.1) would be to use beam-defraction technology. As explained previously, this was not available and the commercial construction of such gratings would have a unit price exceeding £1,000. Instead, specialist gelatine filters, such as those used by photographers and in the Milton Multi-Band Radiometer (Milton, 1980) were used. Using a suitable filter/photo-diode combination the sensors were then tailored to approximate channels 1 and 2 of the AVHRR sensor. Channel 1 (580-680 nm) was approximated in two ways using a Texas Instruments TSL250 Silicon photodiode (spectral response curve 350-1050 nm with a peak at 800 nm, Figure 3.7, curve A). This was filtered using a LEE106 primary red transmitter resulting in only EMR between 600 nm and 1050 nm being detected (Output-1, Figure 3.7, curve B). The output from the TSL260 (spectral response curve 800-1050 nm) was then subtracted from the output of the TSL250 to yield a response a function of reflectance 600-800 nm (Output-2, Figure 3.7, curve C). The comparison of the output of one photo-diode from the other in the pair is possible since the two diodes (TSL250 and TSL260) were mounted as pairs so to achieve the same field of view (Chris Mutlow, RAL, personal communication 1995). AVHRR Channel 2 (735-1100 nm) was simulated using a Texas instruments TSL260 Silicon photodiode (spectral response curve 800-1050 nm with a peak at 920 nm), Figure 3.8. This did not require filtering.

The TSL photo-diodes were selected since they have:

- (i) low voltage requirements;
- (ii) extremely fast response times (360 nsec at 25° C);
- (iii) are relatively cheap (c. £1 each);

(iv) contain integral amplifiers; and

(v) most importantly, show a flat cosine response, i.e. they obey Lambert's Cosine Law.

Their output therefore will be a linear function of received EMR within their FOV irrespective of reflectance angle. Since these photo-diodes normally have a FOV of  $80^{\circ}$ , a field stop consisting of a matt black plastic tube was fitted. The length of the stop was calculated to produce a field of view of c.  $40^{\circ}$  (+/- $20^{\circ}$  of nadir). The stability and cosine correction of these photocells is exceptionally good. Graphs of output voltage vs. supply voltage; supply current vs. output voltage; and normalised voltage output vs. angular displacement are provided in Appendix 3.6.

Each photo-diode pair was then placed on foam-backed PVC plastic and fitted with the red filter and a mounting bracket (protruding from one side). A LEE210 neutral density filter was then fitted as a dust cover (Plate 3.11). The total weight per pair of diodes was approximately 100 g. Each pair was then connected to a Grant Instruments Squirrel data-logger / power system. Screened multi-core cables were used to reduce any mutual cable-current interference. See Appendix 3.7 for circuit diagram. The ARS system was then programmed to acquire data daily at 10:15 and 14:15 local solar time, i.e. the ATSR-2 and NOAA-14 overpass times. This allowed seven separate points of the TF mosaic, at Lomerio and Chapare, to be monitored simultaneously, at both AVHRR channel 1 and 2 simulated bandpasses, per 16-channel logger. At the savanna site, an 8-channel logger allowed three separate points of the savanna mosaic to be monitored simultaneously. The ARS system takes approximately two seconds to complete power-up operations and take readings from the 16 or 8 photo-diodes.

	Seasonal Semi-Deciduous Tropical Forest	Savanna Aborizada	Seasonally Inundated Humid Tropical Forest
Red ρ (φ) (600-800 nm)	7*	3*	7*
NIR ρ (φ) (820-1050 nm)	7*	3*	7*

Table 3.11 Automated Radiometry at the Three Verification Sites

\* sampling locations monitored daily at 10:15 & 14:15

## 3.4.5.2 Calibration and Installation

The need for the initial calibration of instruments and regular re-calibration cannot be over emphasised. The diode pairs were initially calibrated against each other using a 2000 W quartz-halogen lamp obtained from the NERC Field Spectroscopy Unit and were checked again under clear sky conditions in Bolivia. The photo-diodes of each Pair-1 were marked as a datum, and the rest of the paired arrays calibrated against it. Since the input-irradiance / output-voltage correlation for the TSL-series diode is linear (Figure 3.9) calibration coefficients were derived for each diode-pair these are provided in Appendix 3.8. These were rechecked after the apparatus was dismantled (for most diode pairs). Experimentation was also carried out to check for any temperature or supply voltage dependency in the photodiode output using a Farnell Instruments stabilised power supply. No significant dependencies were found (Figure 3.10).

Although the outputs from the ARS photo-diode pairs are directly proportional to the EMR flux density (Figure 3.9) the result is a voltage and not an absolute unit of reflectance. Therefore standardisation of these voltage units needs to be undertaken before they can be compared. This was achieved by positioning one diode pair facing upward in a clearing, i.e. with an unobstructed view of the sky at nadir. This pair would then receive the total irradiance ( $\phi$ ) for both the AVHRR channel 1 and 2 simulated wavelengths. The downward-facing (reflectance-monitoring) diode measurements could then be standardised to a percentage value of the total irradiance received at each wavelength. In this way, all reflectance measurements obtained at a particular site, at a particular time on a cloudless day could be compared. Since optical remote sensing is only possible under cloudless or near-cloudless conditions, this methodology yielded results for comparison to each image-date.

At the two TF sites the eight available photo-diode pairs were therefore deployed as follows:

- (i) upward looking (one pair);
- (ii) viewing an area of soil and low-vegetation, i.e. plants < 10cm in height, (one pair); and

(iii) in understorey mosaics at varying heights between two and 15 m (six pairs).

At the savanna site four photo-diode pairs were available and deployed as follows:

- (i) upward looking (one pair);
- (ii) viewing an area of soil and shrub-grasses (two pairs); and
- (iii) above the canopy of a typical savanna tree at a height of seven metres (one pair).

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I had originally anticipated the deployment of a canopy-understorey-soil reflectancemonitoring system with diode pairs above the canopy as well as within it. To this end a number of methodologies were considered for their suitability as platforms (e.g. tethered weather balloons, scaffold towers and perspex masts). Ultimately all these proved impractical within the context of this research, see Appendix 3.9 for illustrations.

The criteria for the exact location of each verification site was that it should be as heterogeneous as possible, within the 50m radius of the logger cables, not be prone to inundation, and contain a clearing that was never over-shadowed at 10:15 and 14:15. The light environment in these clearings was assumed similar to that at the top of the canopy (Chazdon and Fetcher, 1984a; Chazdon and Fetcher, 1984b). Salminen *et al.* (1983) stress the importance of the accurate mounting of light sensors, but also note that directional sensitivity is far less important within the canopy since photon fluxes tend to be more diffuse. The final consideration was to ensure that each diode-pair acquired independent measurements. A minimum between-pair distance of 5m was established to avoid spatial auto-correlation in the understorey light environment reported by Becker and Smith (1990).

Diode pairs monitoring the understorey were secured to poles which, in turn, were secured to tree boles or branches by a tree climber. Highly accurate levelling was not possible, but the sensor positions were checked with binoculars. The height of each diode-pair was measured using a clinometer. Topographic variations were not accounted for since they were minimal (c. +/- 5m) at all verification sites.

## 3.4.5.3 Seasonal semi-deciduous tropical forest

The ARS was installed at Lomerio on the 22 July 1995. The eight photo-diode pairs were positioned at a heterogeneous site chosen because it contained deciduous and non-deciduous elements within 50 m of the logger. A local tree climber was employed to secure the diode pairs (pairs 6-8) to suitable trees. Unfortunately, by 16 November 1995, diode-pair 1 and 2, were no longer in a clearing at 10:15 due to growth of the canopy (although at 14:15 it remained unobscured). Photo-diode pair 1 and 2 (one unit) were therefore moved on this date to a new clearing, which remained unobscured throughout the rest of the experiment.

Photo-Diode Pair	Mounted	Observing	Height (m)
1	Stake-mounted	Clearing-Sky	1m
2	Stake-mounted	Soil-Litter-Ground Vegetation	< 0.1m in height
3	Pole-mounted	Understorey	<15m >3m
4	Pole-mounted	Understorey	<15m >3m
5	Pole-mounted	Understorey	<15m >3m
6	Beneath a Momoqui- Caesalpinea floribunda	Understorey	>15m
7	Beneath a Carapau- Anadenanthera macrocarpa	Understorey	>15m
8	Beneath a Ajo- Gallesia integrifolia	Understorey	>15m

Table 3.12 Positions of the Diode Pairs at the Seasonal Semi-Deciduous TF

# 3.4.5.4 Savanna Aborizada

The ARS was installed at Las Trancas on the 26 July 1995. The four photo-diode pairs were positioned to monitor the soil-grass mosaic and a savanna tree canopy (Plates 3.10 - 3.12). The logger and power supply were buried and trenches cut for the cables. Although litter-trap monitoring had to be aborted due to local *interest* in this site, the ARS was not tampered with. Cattle did however chewed through cables on several occasions.

Table 3.13 Positions of the Diode Pairs at the Savanna Aborizada

Photo-Diode Pair	Mounted	Observing	Height (m)
1	Stake-mounted	Clearing-Sky	1m
2	Stake-mounted	Soil-Grass	< 0.5m in height
3	Beneath a Curatella americana	Soil-Grass	<1m
4	Above a Curatella americana	Canopy (Curatella americana)	7m

### 3.4.5.5 Seasonally-inundated tropical forest

The ARS was installed at Sajta on the 27 August 1995. The logger site determined the location of the diode pairs at this site. Since flooding was anticipated the logger unit was placed on a 6 m high embankment so that it would not be inundated. The eight photo-diode pairs were then positioned in the adjacent area. I attempted to climb the trees at this site using the sloth-spikes with limited success. A student forester, Eduardo Rivero, volunteered to

### **CHAPTER 3, Ground Verification & Monitoring**

climb the trees if I boasted of his prowess. The diode pairs 6-8 were secured to suitable trees at 15 m height, and their positions checked with binoculars. A tree fall partially destroyed the logger assembly, in January 1996. This resulted in the removal of the logger-power supply unit at this site for one month.

Photo-Diode Pair	Mounted	Observing	Height (m)
1	Stake-mounted	Clearing-Sky	lm
2	Stake-mounted	Soil-Litter-Ground Vegetation	< 0.1m in height
3	Pole-mounted	Understorey	<15m >3m
4	Pole-mounted	Understorey	<15m >3m
5	Pole-mounted	Understorey	<15m >3m
6	Beneath a Palmero <i>Iriartea venricosa</i>	Understorey	>15m
7	Beneath a Charque	Understorey	>15m
8	Beneath a Mora Macho	Understorey	>15m

Table 3.14 Positions of the Diode Pairs at the Seasonally-inundated TF

# 3.5.1.6 Maintenance

Throughout the field campaign, maintenance and repair to the experimental apparatus was constantly necessary. Cables required re-splicing on several occasions after being severed and flooding also caused problems despite the choice of sites. Silicon crystal bags (to capture moisture) were replaced monthly and the accessible (lower) photo-diodes were wiped free of dust on a monthly basis. The neutral density filters (dust covers) were replaced as necessary.



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# CHAPTER 4 MONITORING LARGE-AREA TROPICAL FOREST PHENOLOGY: II -SATELLITE BASED MONITORING

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# CHAPTER 4 MONITORING LARGE-AREA TROPICAL FOREST PHENOLOGY: II -SATELLITE BASED MONITORING

The remote sensing data used to monitor phenological change was derived from two satellite sensor combinations:

- (i) the ERS-2 ATSR-2 1-km dataset provided by the NERC through the Rutherford Appleton Laboratory; and
- (ii) the NOAA-14 AVHRR LAC product from the SAA-NOAA archive and retrieval services at Pasadena (see Appendix 4.1.a).

Only the visible and near infrared spectral bands were utilised. These are shown below in Table 4.1. A more detailed review of these systems was given in section 2.8.1.

Table 4.1 Satellite spectral bands used to monitor phenological change in this research

AVHRR	ATSR-2	
0.58-0.68 µm	0.545-0.565 μm	
0.735-1.1 μm	0.649-0.669 μm	
	0.855-0.875 μm	
	1.58-1.64 μm	

Image preparation and processing took place on a number of platforms in UNIX/IRIX/Windows95 and NT environments. I am indebted to many individuals, for their time and advice, at the University of Leicester (Department of Geography), please see acknowledgements for details.

### 4.1 ACQUISITION OF IMAGE DATA

# 4.1.1 ERS-2 - Along Track Scanning Radiometer-2

Image data from the ATSR-2 was provided in VAX-backup format necessitating a complex extraction program to obtain the header, image data and geo-co-ordinates separately for each image date. The ATSR-2 instrument developed an operating fault and was non-operational from 22-12-95 to 01-07-96. No data were available for this time-period. In total 119 image-products were obtained, falling between 01-07-95 to 01-08-96 inclusive, for the field site areas. The acquisition process can at best be described as inefficient as requests were lost or delayed, on several occasions for months, or were unreadable when the data arrived.

### 4.1.2 NOAA-14 - Advanced Very High Resolution Radiometer

278 AVHRR-LAC scenes, covering the dates 01-07-95 to 31-08-96, were available. Each contained one or more of the field sites. Seven scenes were immediately rejected since they were acquired by the NOAA-12 satellite (and the AVHRR instrument on-board differs significantly in terms of its calibration, orbital-geometry and sensor drift). The resulting 271 scenes were then screened by the processes outlined in section 4.2.

### 4.1.3 Landsat-4 Thematic Mapper

Two relatively cloud-free TM scenes were selected from the archive of data at the University of Leicester, Department of Geography (Table 4.2). These images do not form part of the phenological monitoring time-series and were used only for site location purposes.

Table 4.2 Landsat-4 Thematic Mapper images used in field site location

Scene ID	Date	Field Site	Cloud Cover (%)		
230-071	06-89	Lomerio Las Trancas	5		
230-072	30-08-85	Chapare	2		

### 4.2 PRELIMINARY SATELLITE DATA PROCESSING

### 4.2.1 Scene selection criteria

Given the large number of image dates available for investigation, a screening process was implemented. Its objective was to select, and retain for analysis, only those image dates with the following attributes:

- (i) a high data-rate which equates to a 12-bit digitisation (N.B. this only applies to the ATSR-2 data) (section 4.2.1.1);
- (ii) no cloud-cover, haze or smoke covering the sites (section 4.2.1.2);
- (iii) a near-nadir viewing angle to avoid excessive spatial scale variance and to lessen bidirectional reflectance distortions (section 4.2.1.3); and
- (iv) minimal atmospheric attenuation differences (section 4.2.5).

## 4.2.1.1 Data rate selection

The ERS-2 satellite has an on-board recording facility for use when the satellite is not within the sending horizons of the ESA ground stations at Kiruna (Sweden), Maspalomas (Spain), Gatineau and Prince Albert (Canada). This is the case for South America. The ATSR-2 instrument can be operated in three different modes (High-rate, Low-rate flexible daytime, Low-rate night time) depending on the operational status of the other payload instruments. Only High-rate data is useful in the context of this research, since alone it allows the visible channels at full swath (512 km) and 12-bit digitisation to operate and record. Only day time images with High-rate data are presented in this study. Of the 119 ATSR-2 scenes obtained, only 35 contained high rate coverage of one or more of the field verification areas.

The AVHRR data did not need to be screened in this way since all the requested data was in LAC format (i.e. full swath, 10-bit digitisation with all 5 channels present); 271 image dates were available.

### 4.2.1.2 Cloud cover flagging

The elimination of data containing reflectance measurements affected by cloud is essential. Pixels that are even partially cloud-obscured, or contain areas of cloud shadows, will introduce spurious data (Goward *et al.* 1991). Similar problems occur during the austral winter (July-September) when smoke palls associated with savanna burning are common in eastern Bolivia.

### CHAPTER 4, Satellite Based Monitoring

A number of procedures have been proposed to identify cloud-contaminated pixels. For example, Gutman (1991) and Rosema *et al.* (1992) both propose the use of temperature data from the thermal-IR emitting spectral region (i.e. AVHRR channels 4 and 5, band-passes 10.3-11.3  $\mu$ m and 11.5-12.5  $\mu$ m, respectively) to create a threshold cloud mask at 285K. Other techniques include the use of vegetation indices (Holben *et al.* 1990); cf. section 2.8.2. Vegetation indices are assumed to be negative, or at least significantly lower, when cloud is present. However, since such indices are dependent on view and illumination geometry; thin cirrus clouds, sub-pixel clouds or atmospheric haze may not be detected (Holben, 1986; Goward *et al.*, 1991).

The ATSR-2 data was meant to contain an automatic cloud-clearing/flagging procedure. Unfortunately, this was not available on the RAL data product. Therefore, all images were manually checked. This was achieved by locating the three verification sites and screening for cloud presence at thermal wavelengths using channel 7 (11.5-12.5  $\mu$ m) and by calculation of the NDVI ratio. Since the verification sites are relatively small (consisting of only four to nine pixels) no cloud-mask was produced. Images were only considered viable if the one or more of the verification sites was cloud-free. Of the 35 High-rate images, only 9 ATSR-2 images remained after this screening process. A second iteration of cloud cover flagging was then undertaken. All remaining 9 images were re-screened, this time including a one pixel buffer zone around each site. The purpose of this re-screening was to identify shadows cast from neighbouring cloud-contaminated pixels. All 9 ATSR-2 images remained after this process. It should be noted that within both these cloud flagging procedures, no absolute cut-off rates were determined. The process of cloud cover flagging can best described as subjective, but the affects of cloud cover will be filtered further by the process of temporal compositing (section 4.3).

The AVHRR data was manually checked for cloud presence using the thermal-channel 5 (11.5-12.5  $\mu$ m) and by the calculation of the NDVI ratio. The procedure is out-lined above. Of the 271 AVHRR images 67 remained after checking.

### 4.2.1.3 Selection according view angle

Variations in the sensor view angle and solar illumination angle across a scan line (acrosstrack) or along an orbit path (along-track) can result in different sensor responses from the same targets (Holben and Fraser, 1984; Goward *et al.*, 1991; Figure 4.1). This is particularly true of the AVHRR sensor since its across track dimension is approximately 2700km (2048 pixels). Duggin and Piwinski (1984) report that variance resulting from across track differences may be as high as 10% for sensor view angles greater than +/- 14°. Holben and Fraser (1984); Holben (1986); Singh (1988) and Goward *et al.* (1991) have all investigated the influence of illumination geometry on NDVI and found that it decreased as solar zenith angles increased (Figure 4.2). However, Deering and Eck (1987) report the opposite explaining their findings through reduced shadowing effects. All these studies indicate spectral reflectance changes may result from view and illumination geometry changes alone. These reflectance variations may result from:

- (i) different sensor-target distances through the atmosphere (with resulting differences in atmospheric attenuation and scattering events);
- (ii) different pixel sizes, leading to difficulties in identifying features on the imagery and in geometric registration; and
- (iii) differing proportions of landscape components being integrated into a pixel's spectral signal.

The need in the context of this study is to eliminate (or at least minimise) these variations in the data. A decision was taken therefore to use only the central part of the AVHRR swath, i.e. reject those images where the field verification sites were located towards the edges of the scan-line (across-track). The issue is to determine how much of the central portion of the image should be retained for sampling. Too strict a criterion will result in less images for analysis, while the inclusion of more extreme off-nadir data will act to degrade the fidelity of the dataset. Duggin (1983) recommends use of data +/- 20° of nadir, other authors suggest different thresholds: Tucker *et al.* (1985) +/- 20-35°; Sader *et al.* (1990) +/- 30°; Spanner *et al.* (1990) +/- 28° and Goward *et al.* (1991) +/- 25°.

Since the ATSR-2 swath is comparatively small (c. 500km), across-track variation is minimal (c.  $+/- 21^{\circ}$ ). All 9 images were retained therefore for registration, regardless of verification site location within the swath.

The 67 remaining AVHRR images were investigated to determine the most appropriate across-track view-angle cut-off point. Ultimately three datasets were produced for each verification site:

- (i) where the field site was within  $+/-10^{\circ}$  of nadir;
- (ii) where the field site was within  $+/-20^{\circ}$  of nadir; and
- (iii) where the field site was within  $+/-30^{\circ}$  of nadir.

22 images had one or more sites within  $+/-10^{\circ}$  of nadir, 34 images had one or more sites within  $+/-20^{\circ}$  of nadir, and 53 images had one or more sites within  $+/-30^{\circ}$  of nadir.

Along-track view-angle differences are not accounted for in this procedure. However, these are minimal (Figure 4.1). Variations in solar elevation are also minimal since all sites are within c.  $16^{\circ}$  of the Equator and the satellite is in a sun-synchronous orbit (local solar acquisition time does not vary greatly along or across track within +/-  $30^{\circ}$  of nadir).

### 4.2.2 Spatial degradation of TM data to ATSR-2 / AVHRR scale resolution

When monitoring TF regions with 1-km data, the pixels may contain several land cover types. For example, substantial pockets of deforestation may not be detected within an AVHRR pixel but have significant affects on the reflectance value. To ensure that only pure forest pixels were monitored using the 1-km dataset, Landsat-TM images were employed as an intermediate (spatial resolution) data source between the ground verification sites and the 1-km pixels. Two full TM scenes were spatially degraded from their original 30 m spatial resolution to a 1-km resolution. Inherent in this simulation was the assumption that reflectance from a given area is a linear function of the reflectance of the fractional scene components in the sensor FOV. No attempt was made to introduce the modulating effects of the conical ATSR-2 sensor movement or the Earth's curvature for some portions of the AVHRR swath. Although imperfect, these simulations were sufficient for the location of the field sites (see Figures 3.2 and 3.3) and for the detection of deforestation episodes.

### 4.2.3 Image registration

The inaccessible and ephemeral nature of TF landscapes results in maps being difficult to prepare and they quickly become out-of-date. Coupled with this problem is the difficulty of acquiring numerous accurate GPS measurements (in a statistically meaningful manner) to facilitate rectification. Elvidge and Portigal (1990) and Welch *et al.* (1985) concur with this -108-

view, commenting that some landscapes lack distinct features for use as ground control points and may also have unsuitable or incomplete map coverage. These authors conclude that remotely-sensed images themselves may provide a more accurate co-ordinate reference systems.

Image registration was achieved in two stages. Firstly, the three verification sites were identified on the degraded TM imagery and located on the ATSR-2 and AVHRR datum images. The datum for image registration was the first image which was cloud free (in all three verification areas) in each dataset. For ATSR-2 this was 07-08-95; and for AVHRR this was 21-07-95. Secondly, suitable non-ephemeral features were located, within each image-landscape, for use as conjugate points. All 9 ATSR-2 images were then registered to their datum image. The 53 AVHRR images were co-registered separately to their datum image. The result was two time-series of 1-km<sup>2</sup> imagery, one for ATSR-2, the other for AVHRR.

The accuracy of spatial registration between time-series of image data greatly effects the accuracy of any monitoring process. Townshend and Justice (1988) stress that the impact of mis-registration errors increases rapidly between zero and one pixel and less rapidly thereafter. Great care was taken therefore to ensure image control points were both well distributed and plentiful. A second order (affine) transformation was used in all registration procedures and re-sampling was performed using the nearest neighbour method. The resulting RMS errors were minimal (always less one pixel) and are presented in Tables 4.3 and 4.4. (See appendix 4.2 for details).

Image-Date (in Julian Days) <sup>#</sup> denotes 1995 *denotes 1996	Number of Image Control Points Used in Registration	Total RMSE -Pixels (x & y Residuals)
220#	22	0.122
239#	19	0.137
242 <sup>#</sup> Datum	N/A	N/A
245#	25	0.25
248#	16	0.121
296#	16	0.232
334#	13	0.244
350#	20	0.124
207*	17	0.239

Table 4.3 Registration of the 9 ATSR-2 Images

Image-Date (in Julian Days) <sup>#</sup> denotes 1995 *denotes 1996	Number of Image Control Points Used in Registration	Total RMSE -Pixels (x & y Residuals)
156#	29	0.312
157#	34	0.258
183#	31	0.274
184#	31	0.367
194#	30	0.351
203 <sup>#</sup> Datum	N/A	N/A
205#	30	0.285
220#	31	0.284
222#	27	0.356
223#	31	0.312
232#	21	0.468
233#	26	0.543
239#	29	0.411
240#	28	0.567
248#		0.299
249#	32	0.356
257#	29	0.224
258#	35	0.239
259#	23	0.654
260#	21	0.754
261#	30	0.463
268#	27	0.385
276#	30	0.287
296#	11	0.976
297#	26	0.643
305#	27	0.654
306#	34	0.645
334#	45	0.369
342#	26	0.637
360#	28	0.847
32*	34	0.364
44*	32	0.385
50*	31	0.498
51*	22	0.756
52*	19	0.432
59*	26	0.374
67*	31	0.283
69*	28	0.285
70*	28	0.301
97*	19	0.387
106*	21	0.435
115*	26	0.284
124*	23	0.38
125*	19	0.432
161*	19	0.385
181*	17	0.446
182*	23	0.329
198*	28	0.286
199*	27	0.38
200*	29	0.311
206*	28	0.243
207*	23	0.386
208*	27	0.338

Table 4.4 Registration of the 53 AVHRR Images

### 4.2.4 Creating sub-scenes and radiometric calibration

Sub-scenes containing the verification sites were extracted from the full-scene AVHRR and ATSR-2 images. Since the Lomerio and Las Trancas verification sites are relatively close (c. 14 km) both of these sites were placed on a single set of image sub-scenes.

Radiometric calibration of the ATSR-2 channels was relatively simple, since each is referenced against an on-board calibration target. These calibration coefficients were posted on the ESA ATSR-2 homepage (<u>http://earth1.esrin.esa.it/ERS/ATSR-2cal</u>; 23-09-96) and are provided in appendix 4.3.

Although the pre-launch calibration procedures for the NOAA-14 AVHRR are quite extensive, they are not sufficient however to achieve the desired accuracy for a 1-km multi-temporal dataset (Price, 1987; Conese *et al.*, 1988; Che and Price, 1992). This is since the AVHRR instrument has undergone considerable reductions in sensitivity during its operational lifetime. Exposure to the harsh space environment (Brest and Rossow, 1992) and variations in the satellite's position in orbit may both cause the output in digital counts to vary. Unfortunately, there are no on-board calibration sources for the visible and near infrared channels (1 and 2) and empirical corrections based on unvarying ground targets have been generated to correct the data (NOAA, 1998; D'Souza, 1996).

Channels (1 and 2) were converted to TOA (Top-Of-the-Atmosphere) percentage albedo using the calibration equation described by NOAA (1998); Che and Price (1992) and Spanner *et al.* (1990b). The percent albedo (for sensor channel i) being computed as a linear function of the input data value using the following equation:

$$A_i = S_i C + I_i$$
<sup>[4.1]</sup>

Where:

A<sub>i</sub> is the percent albedo measured in channel i,

C is the input data value in counts,

 $S_i$  is the scaled slope of channel i, and,

I<sub>i</sub> the intercept value.

### 4.2.5 Atmospheric correction

The need for atmospheric correction in phenological studies was emphasised in section 2.8. Corrections in this study were calculated using a revision of the atmospheric radiative transfer code, *simulation of the satellite signal in the solar spectrum* (5S) (Tanré *et al.*, 1990) as recommended by Telliet (1992) and Ranson *et al.* (1994) for the retrieval of surface reflectance from TOA percent albedo. Surface reflectance ( $\rho_s$ ) for a specific wavelength ( $\lambda_i$ ), from top-of-the-atmosphere reflectance  $\rho$  ( $\lambda_i$ ,  $\theta_s$ ,  $\theta_v$ ,  $\Delta \phi$ ) is acquired through two inversion coefficients A ( $\lambda_i$ ) and B ( $\lambda_i$ ), defined as:

$$A(\lambda_i) = \frac{1}{T_g(\lambda_i \theta_s \theta_v) T(\lambda_i \theta_v)}$$

$$(4.2)$$

$$B(\lambda_i) = \frac{\rho_a(\lambda_i \theta_s \theta_v \Delta \phi)}{T(\lambda_i \theta_s)T(\lambda_i \theta_v)}$$
[4.3]

 $\rho_{s}(\lambda_{i})$  is obtained from the following:

$$Y(\lambda_i) = A(\lambda_i)\rho(\lambda_i\theta_s\theta_v\Delta\phi) - B(\lambda_i)$$

$$Y(\lambda_i)$$
[4.4]

$$\rho_s(\lambda_i) = \frac{\Gamma(\lambda_i)}{[1 + S(\lambda_i)Y(\lambda_i)]}$$
[4.5]

Where:

 $T_g(\lambda_i \theta_s \theta_v)$  is the total gaseous transmittance associated with absorption along the solar-sensor atmospheric path,

 $T(\lambda_i \theta_s)$  the atmospheric scattering transmittance along the sun-target atmospheric path,

 $T_g(\lambda_i \theta_v)$  the atmospheric scattering transmittance along the target-target atmospheric path

 $\rho_a(\lambda_i \theta_s \theta_v \phi)$  the atmospheric reflectance, and,

S ( $\lambda_i$ ) the atmospheric spherical albedo;

 $\lambda_i$  the sensor spectral band pass,

 $\theta_s$  the solar zenith angle,

 $\theta_s$  the viewing zenith angle,

 $\Delta \phi$  the relative azimuth angle between the sun and satellite direction.

The spherical albedo and the quantities necessary to calculate  $A_i$  and  $B_i$  were obtained by running the modified 5S code (MacKay *et al.*, 1996). This was inverted using a standard

tropical atmosphere and continental aerosol profiles to pre-compute the Rayleigh optical depth and aerosol scattering and gaseous absorbing parameters (at the band passes of ATSR-2 and AVHRR). Since only cloud free images were used, atmospheric optical depth was user defined at 10% for 550 nm. The inversion procedure (S5) was then run to derive atmospheric correction coefficients for:

- (i) each individual pixel in the verification areas separately (this was possible since the verification sites are small); and
- (ii) a 50 x 50 pixel area, centred on the verification sites, in each sub-scene. The input values for these larger areas were the darkest vegetated pixels.

ATSR-2 Channels VIS-1, 2 and 3 (545-875 nm) and Channel 4 (1600 nm) and AVHRR Channels 1 (580-680µm) and 2 (735-1100 nm) were corrected.

The overall accuracy of atmospheric correction is thought to be good. The 6S code was not used since errors had been reported in its inversion (Dr. George MacKay University of Leicester, *personal communication*). Errors due to the use of a standard tropical atmosphere (e.g. climatological means) and aerosol models rather than date-specific atmospheric optical thickness are thought to be minimal, although they may become significant in the winter fire season when the lower atmosphere aerosol load is particularly high. For an alternate form of the 5S model see appendix 4.4 or for a fuller description see Teillet (1992).

## 4.3 TEMPORAL COMPOSITING OF THE 1-KM RESOLUTION IMAGERY

The Maximum Value Compositing technique (MVC) (Tucker et al., 1985; Holben, 1986), assigns the maximum pixel value acquired during a compositing period to a specific ground area. The advantage of this method is that the undesirable effects of cloud contamination, atmospheric modulation differences and solar-sensor directional effects are attenuated further. Justice and Hiernaux (1986) comment that selecting the maximum NDVI from a successive number of time-series of data, on a per-pixel basis, will effectively minimise noise within the remotely-sensed representation of actual ground conditions. Huete et al., (1992) pp. 151 demonstrate that the maximum values may not always lie at nadir but instead at '...the most off-nadir sun-view arrangements'. Temporal compositing must therefore involve simultaneous consideration of solar-illumination view-reflectance geometries (cf. section 4.2.1.3). Viovy et al. (1992) suggest a Best Index Slope Extraction (BISE) method as an alternative to the MVC. Here a user defined 'sliding period' is introduced to eliminate noise associated with variable scanning geometry and cloud. These authors conclude (in a study using GAC data) a 30-day sliding period for the cloudiest periods of the year in a west African tropical savanna woodland is desirable, whilst noting a 10-day composite period is sufficient to suppress most noise introduced by scanning geometry. Eidenshank and Haas (1992) suggest that mean (rather than maximum) value composited NDVI is most appropriate for phenological applications.

## 4.3.1 Datum creation

The datum for the compositing time-periods was set as 01-06-95. Due to the low total number of ATSR-2 images (nine) and their clustered temporal distribution (see Figure 4.4) temporal compositing was not attempted on these data. Subsequent analysis therefore focuses on the AVHRR data alone.

## 4.3.2 Temporal resolution and composite techniques

The incidence of cloud and the latitude of the study sites (Figure 4.3) may both dictate the most appropriate composite time-period (temporal resolution) and compositing technique. For this reason a number of different temporal resolutions and two compositing procedures were experimented with. A temporal database was assembled for each verification site using the MVC technique (Holben, 1986) and a mean value composite (Eidenshank and Haas, 1992).

Both of these techniques were used to calculate composite reflectance values for temporal periods of 5, 15 and 30 days. These calculations were repeated to derive three datasets for each site. These had a view geometry of: (i) +/- 10-degrees nadir; (ii) +/- 20-degrees nadir; and (iii) +/- 30-degrees nadir. The different data sets are presented in Table 4.5.

	Composite Time-Period	1	Lomerio	-	Lomerio	-	Lomerio	E	Las I fancas	T as Turners	Las I faucas		Las I rancas	Ę	Cuapare		Cuaparc	Chanara	<b>Ullapar</b> c
Degrees +/- Nadir		1	0	2	:0	3	60	1	0	2	0	3	0	1	0	2	,0	30	
	All Images (No. of Images)	8 22		30 7		7	23		31		17		19		34				
Composite Procedure		MVC	Mean-VC	MVC	Mean-VC	MVC	Mean-VC	MVC	Mean-VC	MVC	Mean-VC	MVC	Mean-VC	MVC	Mean-VC	MVC	Mean-VC	MVC	Mean-VC
Degrees +/- Nadir		10	10	20	20	30	30	10	10	20	20	30	30	10	10	20	20	30	30
	5 Days (No. of Images)	8	8	19	19	22	22	7	7	19	19	22	22	16	16	17	17	23	23
	15 Days (No. of Images)	7	7	14	14	16	16	7	7	15	15	16	16	12	12	13	13	15	15
	30 Days (No. of Images)	7	7	11	11	12	12	7	7	12	12	13	13	11	11	11	11	11	11

Table 4.5 Results of the AVHRR Image-Date Selection and Compositing Procedures

Analysis of Table 4.5 reveals view angle selection has had a variable effect on the frequency of useful images. At Lomerio and Las Trancas, view angle selection resulted in a dramatic decline in the number of images available for phenological analysis. The total number of images fell from 31 (at  $\pm 30^{\circ}$  Nadir) to 7 (at  $\pm 10^{\circ}$  Nadir) at Las Trancas, and the

number of 30-day composites fell from 13 to 7. Images for Lomerio show a similar trend. The effects of view angle selection are less pronounced at the Chapare verification site, due to its proximity to the NOAA-14 ground-track. The total number of images dropped from 34 (at  $\pm 30^{\circ}$  Nadir) to 17 at (at  $\pm 10-20^{\circ}$  Nadir).

The temporal distribution of AVHRR images, by verification site, are presented in Figure 4.5. Substantial gaps are evident for some periods of the year, particularly in the cloudier austral summer months. The effects of the view angle selection process (per-verification site) are presented on Figures 4.6 (Lomerio); 4.7 (Las Trancas); 4.8 (Chapare). The  $\pm 30^{\circ}$  Nadir images have been divided into three classes;

- (i) those whose look-angle is less than  $\pm 20^{\circ}$  Nadir (indicated with a solid circle),
- (ii) those with a forward look-angle, i.e. in direction of the sun (indicated with a  $\Box$ ),
- (iii) those with a backward look-angle, i.e. away from the sun (indicated with a  $\wedge$ ).

Since the NOAA series satellites have a similar track across tropical regions once every 11 days (Goward *et al.*, 1991; McGregor and Gorman, 1994; Figure 4.3) composites of less than this time period will contain reflectance-values from differing bi-directional reflectance angles (i.e. the 5-day composite). Moody and Strahler (1994) note that if the composite period is at least a month, such effects will usually be negated since reflectance in the back-scattering direction (BRDF-hotspot) will produce the highest reflectance values due to the reduced shadowing component in these images (Howard *et al.*, 1994). In this context, this research will explore Hill's (1996) contention that look geometry may be more important than spectral phenology in determining reflectance in tropical forests.

# CHAPTER 5 RESULTS AND ANALYSES OF THE GROUND VERIFICATION DATA

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# CHAPTER 5 RESULTS AND ANALYSES OF THE GROUND VERIFICATION DATA

In chapter 3, the methodology for monitoring: microclimatology (using automatic weather stations) and vegetation phenological change (using five techniques) was detailed. The overall aim of these measurements is to facilitate an understanding of spectral phenological changes detected by earth observing systems.

In this chapter, the results of these ground monitoring experiments are presented. Specifically, the observed meteorological patterns recorded at the two AWS are documented (section 5.1) and the results of the phenological monitoring analysed (section 5.2).

# 5.1 OBSERVED METEOROLOGICAL PATTERNS

The purpose of monitoring meteorological variables in this study was to quantitatively evaluate the trends in the satellite-derived and ground-observed phenological data.

Meteorological data are presented at two time scales.

- (i) Daily: consisting of seven monitored parameters (net radiation, total radiation, air temperature, wet bulb depression, wind speed, wind direction and precipitation) and two derived meteorological parameters (relative humidity and potential evaporation). In addition, accumulated daily rainfall was determined.
- (ii) Monthly: comprising mean, maximum and minimum values of all seven monitored, and the two derived, meteorological parameters (Tables 5.1.1 and 5.1.2). In addition, mean monthly potential evaporation was subtracted from total monthly precipitation to provide an estimate of the water available to vegetation.

# 5.1.1 Las Trancas

The meteorological data recorded at Las Trancas indicate a climate with a pronounced dry season, of approximately 5 months, during the austral winter (May to September). The annual precipitation of 1150mm was highly seasonal (90% of occurring from October to March). Mean annual rainfall in the surrounding area varies from 700-1500mm p.a. (BOLFOR, 1995c). The mean monthly temperature varied only slightly throughout the year, reaching a minimum of 22.7 °C in June and a maximum of 25.4 °C in November (Table 5.1).

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	Maximum Mean Daily Air Temperature (° C)	Minimum Mean Daily Air Temperature (° C)	Mean Monthly Air Temperature (°C)	Monthly Precipitation (mm)	Mean Monthly Relative Humidity (%)	Mean Monthly Penman (Potential) Evaporation Estimate (mm Day <sup>-1</sup> )	Mean Monthly Midday Net Radiation (W m <sup>-2</sup> )	Mean Monthly Midday Total Solar Radiation (W m <sup>2</sup> )
January	26.4	23.6	24.7	187	89	123	751	1094
February	26.2	23.5	24.7	129	90	139	729	1099
March	26.9	22.8	24.2	225	89	127	758	1114
April	25.1	22.1	23.9	100	82	154	798	1159
May	25.3	20.1	23.3	14	76	182	789	1163
June*	23.9*	20.9*	22.7*	4*	76*	207*	781*	1105*
July*	25.1*	20.4*	23.7*	0*	58*	493*	793*	1103*
August	24.9	20.9	22.9	0	53	480	767	1083
September	26.6	20.1	23.5	19	75	263	780	1067
October	25.8	21.5	23.8	48	82	131	763	1023
November	27.4	22.8	25.4	149	84	140	751	1039
December	25.9	22.6	24.6	291	87	113	765	1082
Annual Mean / Total	27.4*	20.1*	23.9*	1166	7 <b>8</b> .42	2552	768.75	1094.25

Table 5.1 Summary of the meteorological data collected at Las Trancas

\*Incomplete data / extrapolation necessary see Appendix 5.1.1

Relative humidity and potential evaporation were calculated daily (section 3.4). The AWS system uses the standard Penman equation for estimating free-water evaporation based on empirical coefficients derived from the daily net radiation budget, relative humidity and wind-speed. This provides an estimate of potential evaporation. This estimate may be erroneous however for a savanna-type climate that has a very strong seasonal hydrological component. Wellens (1997) successfully used water balance, and estimates of actual transpiration, for comparison with rangeland phenological data. The calculation of water balance was not attempted here however since no reliable transpiration (or soil moisture) data were available. Instead an estimate of water availability was made by subtracting potential evaporation from monthly precipitation totals (Figure 5.5).

Both Boaler (1966) and Malaisse (1974) recommend that meteorological records be divided into distinct seasons for comparison with phenological data. Such a division has some merit at Las Trancas where a marginally hotter, and significantly more humid, wet season is evident in the austral summer, and a slightly cooler, less humid dry season is found in the
austral winter. Precipitation, relative humidity and potential evaporation data all accurately define these seasons; which is unsurprising as all these parameters are dependent on the amount of available water in the environment (Figures 5.1-5.5).

## 5.1.2 Chapare

The AWS in Chapare recorded meteorological data characteristic of a humid tropical climate with a moderate year-round rainfall (Table 5.2). A mean annual precipitation of 3651 mm was recorded, most (65%) falling in the austral summer (November to March). Mean monthly temperature varied slightly throughout the year, reaching a minimum of 23.9 °C in May and a maximum of 26.1 °C in January.

	Maximum Mean Daily Air Temperature (° C)	Minimum Mean Daily Air Temperature (° C)	Mean Monthly Air Temperature (° C)	Monthly Precipitation (mm)	Mean Monthly Relative Humidity (%)	Mean Monthly Penman (Potential) Evaporation Estimate (mm Day <sup>-1</sup> )	Mean Monthly Midday Net Radiation (W m <sup>2</sup> )	Mean Monthly Midday Total Solar Radiation (W m <sup>2</sup> )
January	27.9	24.1	26.1	654	85	119	767	1071
February	27.7*	23.5*	25.1*	496*	85*	109*	751*	1069*
March	26.9*	23.1*	24.3*	392*	86*	121*	768*	1058*
April	27.5	21.8	24.2	263	86	119	789	1104
May	27.4	21.5	23.9	190	<b>8</b> 5	116	783	1084
June	26.9	23.1	25.4	134*	82	97	758	1098
July	-	-	-	-	-	-	-	-
August	-	-	-	-	-	-	-	-
September	26.8*	21*	21.4*	225*	75*	104*	782*	1075*
October	28.6	21.5	25.1	311	77	122	784	1049
November	27*	22.8*	25.3*	415*	80*	86.5*	781*	1057*
December	27.8*	22.6*	26*	405*	83*	119*	775*	1073*
Annual / Mean	28.6	21	24.5*	3651*	81.7*	1257*	775.27*	1072.5*

Table 5.2 Summary of the meteorological data collected at Chapare

\*Incomplete data / extrapolation necessary See Appendix 5.1.1

The potential evaporation estimation (calculated using Penman's equations) is likely to be much more accurate at this station since the inundated forest vegetation in the surrounding area more closely approximates a freely evaporating water surface. Several sources of error were noted.

- (i) The rain-gauge overflowed on at least one occasion; pointing towards a potential underestimation of rainfall particularly during the austral summer (Figures 5.6; 5.7 and 5.9).
- (ii) The wet bulb reservoir dried-out during October and November 1995. The calculation of relative humidity was therefore susceptible to a systematic error, the RH increasing artificially to 100% as the wet-bulb reservoir evaporated.
- (iii) Periods of data loss occurred due to rodents chewing through the cable from the solar panel. Data for these periods had to be extrapolated (see Appendix 5.1 for details).

The division of the meteorological year into distinct seasons at this site was not appropriate. Although the hydrologically dependent variables (e.g. precipitation, Figure 5.6 and 5.7, relative humidity and potential evaporation, Figure 5.8) show seasonal variation, the availability of water was never in deficit (Figure 5.10). Consequently, a lack of water is unlikely then to be a factor controlling phenology at Chapare. However, seasonal water stresses may occur in the canopy where fluctuations in relative humidity and potential evaporation will be much greater than at the near surface level (1-2 m) monitored by the AWS.

## 5.2 PHENOLOGICAL MONITORING

This section details the results of the five methods employed to monitor phenology at the three ground verification sites. These were:

- (i) litterfall, monitored using basket traps and small clearings;
- (ii) visual assessments of phenological stage;
- (iii) canopy openness monitored using ground-based hemispherical photography;
- (iv) changes in canopy LAI observed using a Ceptometer;
- (v) changes in the reflectance of ground, understorey and savanna vegetation as monitored using an automatic radiometry system.

Associations between seasonal vegetation phenology and meteorological parameters are also discussed. Suggestions are then made about the abiotic parameters that may be influential in large-scale phenological-change.

## 5.2.1 Litterfall weights and LAI calculations

Litterfall was collected monthly at two verification sites (the seasonal deciduous TF and the seasonally-inundated TF). Samples were dried, split into categories (i.e. leaves; wood, twigs and branches; fruits; flowers; epiphytes, and frass) and weighed. The dry weights were then adjusted for their respective projected ground-areas  $(22m^2)$  for the total-litterfall clearings and 6m<sup>2</sup> for the fine-litterfall traps). This resulted in an estimates of litter loss in grams per m<sup>-</sup> <sup>2</sup> per month (Figures 5.11 and 5.13). Total litterfall as well as leaffall, woodfall, fruitfall and flowerfall are shown on these graphs. In addition, daily litterfall was calculated (in grams per m<sup>-2</sup> per day) by dividing the total monthly litter weight by the number of collection days (Figures 5.12 and 5.14). This daily data shows a far greater within group variability than was anticipated. This is probably because litter losses from individual sample points due to wind and/or decomposition may be substantial and unlikely to be spatially or temporally constant (Kunkel-Westphal and Kunkel, 1979). However, even if it is assumed that such losses were low, a large within-site variance is unsurprising given that the spatial variance in phenological phenomena at a community-level is an integration of many diverse abscission strategies. Individual plants and species will each respond to local microclimatic conditions in a unique manner. In addition, microclimatic conditions are variant within the verification sites. As a consequence, at the spatial scale of a single collection point or trap, individual plant responses will dominate monitored litter losses and a high within site variance is to be expected.

Problems were encountered in the calculations of leaf area using a 10% sample of leaflitter weight using a standard hole-punch (after Marshall, 1968). Differences in the petiole (stalk) to blade ratio between simple leaves; pinnately-compound leaves (those whose leaflets originate from a central midrib) and palmately-compound leaves (those whose leaflets originate in a single point and radiate fan-wise) resulted in no significant regression being established. This is because the proportions of each of these respective leaf types differed from trap to trap due to site heterogeneity. Therefore only the dry weights of total and leaf litter at each site were used to investigate the associations between meteorological and litterfall parameters.

## **Annual litterfall**

Measurements of the annual litterfall (and leaffall) from the semi-deciduous TF and seasonally-inundated TF are comparable to similar studies conducted around the world (Table 5.3). Lowland TFs have a higher annual turnover of leaves than sub-tropical TF ecosystems. In this context, the relatively low annual litterfall for Chapare is surprising. It must be

## CHAPTER 5, Ground Verification Results

remembered, however, that the forest formations here are a mosaic of successional stages characterised by a substantially lower biomass than is common in more mature lowland tropical forests.

Location / Tropical Forest Type	Total Litterfall (Kg ha Year-1)	Leaffall (Kg ha Year-1)	LAI Canopy	LAI Understorey	Leaf Life (Years)	Reference
Lowland						
Cote d' Iviore	8,200	-	-	-	-	Bernhard (1970)
Brasil	8,040					Dantas (1989)
Nigeria	-	4,500-7,200	-	-	-	Hopkins (1966)
Ivory Coast	-	-	8-10	-	-	Huttel and Bernhard- Reversat (1975)
Cambodia	-	-	5.8	1.6	-	Hozumi <i>et al.</i> (1969)
Malaysia	7700	-	6.87	0.95	1	Kira (1978)
Malaysia	7,500	740-1,020*	-	-	-	Gong (1982); Gong and Ong (1984)*
Panama	-	-	10.6	-	-	Golley <i>et al.</i> , (1975)
Ghana	9,700	-	-	-		John (1973)
Brasil	5400	-	-	-	c. 1.5	Klinge <i>et al.</i> , (1975)
Brasil	5,500	-	-	-	-	Fittkau & Klinge (1973)
Brasil	5.,600-8,000	-				Klinge (1977)
Guatemala	10,000	-	-	-	-	Kunkel- Westphal and Kunkel (1979)
Hong Kong	12,000	-	-	-	-	Lam and Dudgeon (1985)
Belise	12,000	-	-	-	-	Lambert et al., (1980)
Mexico	6580					Martinez- Yrizar (1990)
Thailand	-	-	16.6	-	-	Ogawa et al., (1961)
Bolivia Chapare	5421	2485				This Study
Subtropical						
New Zealand	-	6230	-	-	-	Cowan & Waddington (1991)
India	3,440-4,180	2,880-3,600	-	-	-	Rai and Proctor (1986)
Australia	5,000	-	-	-	-	Webb <i>et al.</i> , (1970)
Bolivia Lomerio	9918	4783				This Study

Table 5.3 A comparison of annual litterfall collections in tropical forests

#### **CHAPTER 5, Ground Verification Results**

Comparison of annual totals of litterfall are of limited value however due to the difficulty of comparison between forest classification schemes, the diversity of collection and measurement methods, and differing lengths of sampling periods (Kunkel-Westphal and Kunkel, 1979).

In order to determine the most significant meteorological influences on litter production, monthly litterfall and monthly leaffall were compared to the following meteorological parameters:

- (i) mean monthly dry bulb temperature;
- (ii) monthly precipitation;
- (iii) mean monthly relative humidity;
- (iv) mean monthly potential evaporation; and
- (v) accumulated daily precipitation.

Only total litterfall and leaffall were selected for correlation analysis since these alone will have a significant affect on the remotely sensed reflectance signals. To test for timedependant associations between the independent (meteorological) and dependant (litterfall) measurements, correlations were calculated with the previous month's meteorological data, the previous two months meteorological data, the subsequent month's and subsequent 2month's data (Cowan and Waddington, 1991). At this stage of the investigation, the search for associations between phenological parameters and potential triggers was confined to linear bivariate analysis. This was felt prudent since the use of higher order polynomials could not be justified from a theoretical standpoint and could possibly produce misleading conclusions (i.e. type-1 errors). Parametric procedures (such as Pearson's Product Moments) represent the most powerful correlation techniques, but are only suitable for use with normally distributed measurements. This technique was employed successfully at the seasonal semi-deciduous TF site. However, both the meteorological and litterfall data from the seasonally-inundated TF are not normally distributed (Figures 5.6 - 5.10; 5.13). Non-parametric correlation (e.g. Spearman's Rank Correlation) were used for the analysis at this site. The Spearman's Rank Correlation is included (for comparison only) at the semi-deciduous TF site. Two-tailed tests were used since no assumptions about the direction of the relationship could be made. Due to the relatively small numbers of observations (i.e. 10-13 in the monthly data) an r-value (or Spearman's rho) of greater than  $\pm 0.7$  (at 95% significance) was considered indicative of an important association.

#### 5.2.1.1 Seasonal semi-deciduous tropical forest site

Litterfall at Lomerio occurs throughout the year, but a single seasonal peak dominates the pattern. The dry winter season (May-September) is the most important litterfall period, accounting for 66% of the annual litterfall (Figure 5.11). Leaffall is the most seasonally variable litterfall component, its phase being synchronous with that of total litterfall although its variance is greater. In contrast, woodfall is less seasonal. Dry season woodfall losses tend to be dominated by the shedding of higher order branches, whilst in the austral summer (wet season) storms and intense precipitation cause the abscission of a smaller number of larger and heavier wood litter components (e.g. a branchfall episode is clearly seen in Figure 5.11). Flowerfall and fruitfall are very small in terms of the total litterfall. Nonetheless, seasonal trends are apparent, the beginning and end of the dry season being the main periods for antithesis and fruiting. Flowers and fleshy fruits are likely to be under-represented in the litterfall collected due to loss from the trap by wind blow and because they are an important food source.

#### Associations between litterfall and meteorological parameters

Correlations between mean monthly temperature and monthly total litterfall and leaffall (Table 5.4; Figures 5.15 - 5.17) showed a significant negative association between the variables, i.e. as temperature declines litterfall and leaffall increase and vice versa. These associations were strongest at a lag of -1 month (the highest correlation being 0.71 at 95% significance). The preceding month's temperature may be an important trigger to total litterfall and leaf abscission at the semi-deciduous TF site.

#### Table 5.4

Correlatio	ns between	n mean monthly	y temperature v	s. monthly	total litterfa	ll and leaffall

	Mean Monthly Temperature vs. Monthly Total Litterfall	Mean Monthly Temperature vs. Monthly Total Litterfall	Monthly Mean Temperature vs. Monthly Leaffall	Monthly Mean Temperature vs. Monthly Leaffall
Lag	Pearson's Product Moment	Spearman's rho	Pearson's Product Moment	Spearman's Rho
2	-0.678*	-0.674*	-0.505	-0.629*
1	-0.665*	-0.642*	-0.504	-0.743**
0	-0.704*	-0.743**	-0.55	-0.779**
-1	-0.71*	-0.597	-0.702*	-0.542
-2	-0.113	-0.032	-0.222	-0.141

Correlations between monthly precipitation and monthly total litterfall and leaffall (Table 5.5; Figures 5.18 - 5.20) demonstrate a significant, negative association that is strongest at a lag of +1 month, i.e. litterfall is high when the subsequent months rainfall is low and *vice versa*. Leaffall did not exhibit a similar trend. This is an interesting association since it implies that at a community level, litterfall may occur prior to a change in the precipitation pattern (i.e. a subsequent dry month).

#### Table 5.5

	Monthly Precipitation vs. Monthly Total Litterfall	Monthly Precipitation vs. Monthly Total Litterfall	Monthly Precipitation vs. Monthly Leaffall	Monthly Precipitation vs. Monthly Leaffall
Lag	Pearson's Product Moment	Spearman's rho	Pearson's Product Moment	Spearman's Rho
2	-0.59	-0.646*	-0.479	-0.705*
1	-0.742**	-0.808**	-0.576	-0.79**
0	-0.702*	-0.664*	-0.582	-0.747**
-1	-0.377	-0.278	-0.47	-0.369
-2	0.014	0.05	0.175	0.05

Correlations between monthly precipitation and monthly total litterfall and leaffall

\*Indicates 95% Significance \*\*Indicates 99% Significance

Associations between relative humidity and monthly total litterfall and leaffall (Table 5.6; Figures 5.21 - 5.23) show highly significant strong negative correlations. Like those of precipitation, these were also greatest at a lag of +1 month. A clear linear relationship is seen in Figure 5.23 with high litterfall and leaffall occurring during of low relative humidity and *vice versa*.

Table	e 5.6	Correlations	between	mean	monthly	relative	humidity	and	monthly	total	litterfall
and 1	eaffa	11									

	Mean Monthly Relative Humidity vs. Monthly Total Litterfall	Mean Monthly Relative Humidity vs. Monthly Total Litterfall	Mean Monthly Relative Humidity vs. Monthly Leaffall	Mean Monthly Relative Humidity vs. Monthly Leaffall
Lag	Pearson's Product Moment	Spearman's Rho	Pearson's Product Moment	Spearman's rho
2	-0.77*	-0.862**	-0.65*	-0.821**
1	-0.927**	-0.732*	-0.931**	-0.755**
0	-0.475	-0.489	-0.492	-0.603*
-1	-0.176	-0.179	-0.242	-0.294
-2	-0.067	-0.22	-0.007	-0.188

#### **CHAPTER 5, Ground Verification Results**

Potential Evaporation (Table 5.7; Figures 5.24 - 5.26) also shows a strong (positive) correlation with litterfall (and leaffall). Again, this is greatest at a lag of +1 month. Interestingly, the regression lines derived for total litterfall and leaffall (Figure 5.26) are different; leaffall being far more sensitive to changes in evaporation than total litterfall. This may suggest a mechanism for stimulating leaf abscission at this site. Givnish (1978) and Cain *et al.* (1956) both note a similar association with compound leaf senescence in deciduous TFs. Table 5.7 Correlations between mean monthly potential evaporation and monthly total litterfall and leaffall

	Mean Monthly Potential Evaporation vs. Monthly Total Litterfall	Mean Monthly Potential Evaporation vs. Monthly Total Litterfall	Mean Monthly Potential Evaporation vs. Monthly Leaffall	Mean Monthly Potential Evaporation vs. Monthly Leaffall		
Lag	Pearson's Product Moment	Spearman's rho	Pearson's Product Moment	Spearman's Rho		
2	0.709*	0.715*	0.639*	0.788**		
1	0.897**	0.797**	0.962**	0.797**		
0	0.466	0.62*	0.506	0.729*		
-1	0.04	0.323	0.022	0.405		
-2	-0.119	-0.41	-0.12	-0.105		

\*Indicates 95% Significance

\*\*Indicates 99% Significance

The above correlations indicate that maximum litterfall may occur prior to the period of: high evaporation, low relative humidity and little rainfall. Givnish (1978) and Ewel (1976) both comment on similar results concluding that such a litterfall timing is advantageous in a seasonally dry climate. This is because leaf area reductions prevent water deficits occurring in the vegetation (e.g. Alvim and Alvim, 1978; Borchert, 1980; Reich and Borchert, 1982; Borchert, 1994a). Leaffall at Lomerio is particularly sensitive to changes in evaporation strengthening this argument. The reduction of large leaf areas is often achieved by the shedding of high order branchlets (and compound leaves). These were observed in the dry season woodfall. Addicott (1978) explains the biochemistry of such abscission episodes observing that the hormone abscisic acid (which promotes leaf senescence and petiole termination) is deployed preferentially into those leaves whose evapotranspirational losses are greatest. Daily accumulated precipitation when compared to daily total litterfall and leaffall, failed to produce any significant correlations. This is probably due to the incompatibility of comparing monthly derived litterfall data (resampled into daily units) with daily precipitation totals.

#### Summary

Meteorological factors containing a hydrological term are the most significantly correlated with leaffall and total litterfall at the seasonal semi-deciduous TF site. These associations are strongest at lag of +1 month indicating that these TF formations may pre-empt changes in hydroclimate with litterfall. Although it was not possible to assign litterfall to a particular stratum it seems likely that the more seasonal canopy microclimate will have the greatest water deficits. Therefore, litterfall and leaffall will be greatest from the canopy during the dry season.

## Table 6.10.... Image: Comparison of the set of

Litterfall at the seasonally-inundated TF site has bimodal distribution (Figure 5.13). The two peaks are found during the short drier winter season (August to October) and in the middle of the wet season (February). Leaffall is less seasonally variant than total litterfall, although a seasonal trend is apparent. The seasonal cycle of woodfall is synchronous with that of total litterfall the wet season peak being particularly high. Flowerfall, and fruitfall, make up a larger percentage by weight than at the semi-deciduous TF site, indicating either a better survival rate in the traps or a greater abundance of these litter components. A weak late wet season peak in flowerfall and fruitfall is noted, although flowers and fruits were recorded for all collection dates.

## Associations between litterfall and meteorological parameters

Despite the seasonal changes in litter production no significant correlations could be found between mean monthly temperature, monthly precipitation, relative humidity, potential evaporation and total litterfall or leaffall (Tables 5.8 and 5.9).

However, it is note worthy that litterfall peaks occur in the driest and wettest parts of the year. A possible explanation was hinted at in section 2.2.3. Namely, that the soils at the site are alluvial, poorly-drained Inceptisols characterised by a low pH and prone to seasonal inundation. Wet season saturation of these soils may cause anaerobic conditions in the rooting

zone with associated increases in soluble ammonium, phosphorus, manganese and ferrous iron levels. These factors may then precipitate rapid leaf senescence and abscission (Pires and Prance, 1985). Adis *et al.* (1979) note a similar temporal distribution of litterfall in an Amazonian inundation forest (*Igapó*), leaffall being twice as high during the inundation phase than during the dry-season. Other authors (e.g. Lam and Dudgeon, 1985; Klinge, 1977) have noted associations between litterfall peaks and very low and very high precipitation events.

Table 5.8 Correlations between mean monthly temperature, precipitation and monthly total litterfall and leaffall

	Mean Monthly Temperature vs. Monthly Total Litterfall	Mean Monthly Temperature vs. Monthly Leaffall	Monthly Precipitation vs. Monthly Total Litterfall	Monthly Precipitation vs. Monthly Leaffall
Lag	Spearman's rho	Spearman's Rho	Spearman's Rho	Spearman's rho
2	-0.083	-0.167	0.417	0.3
1	-0.017	0	-0.083	-0.283
0	-0.183	-0.367	0.3	-0.2
-1	0.76	-0.091	-0.152	-0.333
-2	-0.406	-0.32	-0.6	-0.588

\*Indicates 95% Significance \*\*Indicates 99% Significance

Table 5.9 Correlations between mean monthly relative humidity and potential evaporation vs. monthly total litterfall and leaffall

	Mean Monthly Relative Humidity vs. Monthly Total Litterfall	Mean Monthly Relative Humidity vs. Monthly Leaffall	Mean Monthly Potential Evaporation vs. Monthly Total Litterfall	Mean Monthly Potential Evaporation vs. Monthly Leaffall			
Lag	Spearman's rho	Spearman's rho	Spearman's Rho	Spearman's rho			
2	-0.043	-0.231	0	-0.203			
1	-0.51	-0.145	0.288	-0.085			
0	-0.094	-0.434	0.539	0.186			
-1	-0.437	-0.154	-0.325	-0.607			
-2	-0.685*	-0.401	-0.202	0.215			

	-	% Annual Litter Production Dry Season	% Annual Litter Production Inundated Season	% Annual Litter Production
<b>Igap</b> ó	Leaves	24	55	79
	Wood	8	8	14
	Fruits	0.6	6.4	7
	Total	33	67	100
Chapare	Leaves	33	15	47
(data from	Wood	10	17	27
this study)	Fruits	3	6	9
	Total	71	29	100

Table 5.10 Annual litter production in an inundated forest, after Adis *et al.* (1979), compared to the litterfall at Chapare (seasonally inundated TF)

## Summary

The correlations between the meteorological variables and litterfall measurements were low and not significant at this site. This is perhaps unsurprising given that the monitored climatic parameters did not exhibit a great seasonality. However, it probably also indicative, that at a large area scale, this site has a leaf abscission strategy that is not well synchronised (i.e. a low incidence of deciduous species) and that the canopy is semi-evergreen. Anaerobic soil conditions, associated with inundation, are a possible explanation of the bimodal abscission stratagem (noted in the litterfall collections).

## 5.2.1.3 Conclusions

Litterfall and leaffall exhibited highly significant associations with meteorological parameters at the seasonal semi-deciduous TF site. Litterfall is timed so as to reduce water losses in the driest part of the year. At the seasonally-inundated TF site, no correlations could be established between litterfall or leaffall and the meteorological parameters. Two distinct peaks in litterfall were noted however which have a link to periods of maximum and minimum precipitation.

## 5.2.2 Visual assessments of phenological condition

In this section, visual assessments, of the dominant phenological stage, of representative individual plants and TF strata are presented for each verification site. These observations evolved over the period of the study and are presented here in the form of presence / absence data (see section 3.3.2). Five (presence / absence) classes were derived from observations of: (i) fruiting; (ii) flowering; (iii) leaf senescence; (iv) leaf flushing; and (v) the presence of photosynthetically-active leaves. These were correlated against: (a) mean monthly dry bulb temperature; (b) monthly precipitation; (c) mean monthly relative humidity; and (d) mean monthly potential evaporation. Zar (1974) recommends a Point Biserial correlation analysis that allows for the comparison of *dependant* binary (presence or absence) data with continuously varying *independent* variables (i.e. the meteorological parameters). The result is a correlation coefficient ranging from +1 to -1 that may be interpreted in a similar manner to the correlation coefficients used in the previous section. To test for time-dependant associations, correlations were lagged with the previous month's meteorological data, the previous two months meteorological data and the subsequent month's meteorological measurements.

Since this thesis seeks to understand large-area TF phenology, the individual plant observations (Table 5.11) were combined to provide a two-strata summary response (i.e. ground stratum and sub-canopy/canopy stratum) for statistical analysis. Only associations between monthly leaf flush, leaf senescence and leaf presence and the meteorological variables were investigated since leaves will be the main TF reflectance component in any remotely sensed signal.

## **CHAPTER 5, Ground Verification Results**

Table 5.11 Direct observations of phenology at the seasonal semi-deciduous tropical forest

			1	1995 1996									
* ✓ X	phenological parame phenological parame no data (other pheno no data (individual d	leaves absent leaves emergent leaves expanded leaves senescent	September	October	November	December	January	February	March	April	May	June	
	a de alatra	Ground 1	Emergent/Expanded (20)	2	3	3	3	3	3	3	3	3	2
	Local Name	Garabatá	Flowering	×	×	x	x	x	×	x	x	x	×
	Scientific Name	Pseudoannanas sagenarius	Fruiting	~	1	x	×	x	×	×	x	x	×
Family	Family	Bromeliaceae	Absent Senescent	4	-	-	-	-	-	-	-	-	-
		Ground 2	Emergent/Expanded. (2/3)	3	3	3	3	3	3	x	x	x	x
		Sirarí	Flowering	x	x	x	x	x	x	x	x	x	x
		Peltogyne sp.	Fruiting	×	x	x	×	x	x	x	x	x	x
		Caesalpinoideae	Senescence (1/4)	-	-	-	-	-	-	x	x	x	x
		Ground 3	Emergent/Expanded (25)	3	2	3	2	3	3	3	x	x	x
		Immature Soto	Flowering	x	x	x	x	x	x	x	x	x	x
		Schinopsis cf. brasiliensis	Fruiting	×	x	x	x	x	x	x	x	x	x
		Anacardiaceae	Senescence (1/4)	4	4	-	-	-	-	-	x	x	x
		Canopy 1	Emergent/Expanded (2/3)	-	2	3	3	3	3	x	x	x	X
		Curupaú	Flowering	x	x	x	x	x	×	x	x	x	x
		Anadenanthera macrocarpa	Fruiting	×	x	x	x	×	x	x	x	x	x
		Mimosoideae	Senescence (1/4)	1	1	-	-	-	-	x	x	x	x
		Canopy 2	Emergent/Expanded	2	2	2	3	3	3	3	3	-	-
		Momoqui	Flowering	x	x	x	x	x	x	x	×	x	x
		Caesalpinea puluviosa / floribunda	Fruiting	x	x	x	x	×	x	x	x	x	x
		Caesalpinoideae	Senescence (1/4)	1	-	-	-	-	-	-	4	4	4
		Sub-Canopy	Emergent/Expanded (2/3)	-	-	2	2	3	3	3	3	-	-
			Flowering	x	x	x	x	x	x	x	x	~	~
			Fruiting	1	~	x	x	x	x	×	x	x	~
			Senescence (1/4)	1	1	-	-	-	-	-	4	4	4
		Ground	Emergent/Expanded (2/3)	2	3	3	3	3	3	3	3	3	2
			Flowering	x	ж	×	х	×	x	x	x	x	x
			Fruiting	~	1	x	x	x	x	x	x	x	x
			Senescence (1/4)	4	-	-	-	-	-	-	-	-	-

\*Selective logging at this site affected some of these observations from March 1995 onwards - 132 -

#### 5.2.2.1 Seasonal semi-deciduous tropical forest

## Ground stratum (Figure 5.28):

Although this stratum was never completely devoid of foliage during the monitoring period, significant leaf senescence and abscission was noted at the end of the dry season (September-October). The emergence of new leaves was also clearly seasonal, a major flush occurring contemporaneously with the main period of leaffall. Only one period of fruiting was noted, again at the end of dry season. No antithesis (flowering) was observed.

## Sub-canopy / canopy stratum (Figure 5.29):

The canopy stratum possessed many photosynthetically active leaves between November and April. From May onwards some trees in the upper tree stratum shed their leaves and leaf senescence and abscission continued to occur until late in the dry season, when the forest canopy reached its most open. It was, however, never completely bare. Fruiting was noted during the dry austral winter months (June-October) and flowers were noted at the beginning of this season (May-June). The majority of trees expanded most of their leaves early in the wet season. Although trees in some sections of the monitored forest flushed leaves during other periods, most notably those in the more humid microenvironments (i.e. adjacent to streams and in depressions).

## Associations between phenological observations and meteorological parameters

Significant correlations were found between leaf flushing in the ground vegetation and mean monthly relative humidity, and monthly potential evaporation (Tables 5.12 and 5.13; Figures 5.30 - 5.33). These associations were greatest at lags of zero and -1 month. A lack of correlation between the canopy stratum flushing and meteorological parameters was also noted.

Table 5.12			
Correlations	between	mean	mont

	Monthly Mean Temperature vs. Monthly Ground-Layer Leaf Flush	Monthly Mean Temperature vs. Monthly Canopy Leaf Flush	Monthly Precipitation vs. Monthly Ground- Layer Leaf Flush	Monthly Precipitation vs. Monthly Canopy Leaf Flush		
Lag	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation		
1	-0.247	0.478	-0.478	0.656*		
0	-0.646*	0.669*	-0.566	0.556		
-1	-0.69*	0.284	-0.585	-0.096		
-2	-0.272	-0.367	-0.341	-0.428		

Correlations between mean monthly to	emperature and	precipitation vs.	monthly leaf flush
--------------------------------------	----------------	-------------------	--------------------

Table 5.13 Correlations between mean monthly relative humidity and potential evaporation vs. monthly leaf flush

	Monthly Mean RelativeMonthly MeanHumidity vs. MonthlyRelative Humidity vs.Ground-LayerMonthly CanopyLeaf FlushLeaf Flush		Monthly Potential Evaporation vs. Monthly Ground-Layer Leaf Flush	Monthly Potential Evaporation vs. Monthly Canopy Leaf Flush
Lag	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation
1	-0.619	0.367	0.61	-0.293
0	-0.682*	0.227	0.87**	-0.354
-1	-0.772*	0.11	0.684*	-0.233
-2	-0.356	-0.016	0.38	-0.068

\*Indicates 95% Significance \*\*Indicates 99% Significance

Canopy stratum leaf presence is significantly correlated with mean monthly temperature, monthly precipitation and monthly relative humidity (Tables 5.14 and 5.15; Figures 5.34 - 5.37). All correlations were greatest at lags of zero and -1 month. Ground stratum leaf presence produced significant associations with mean monthly relative humidity and mean monthly potential evaporation (Figures 5.36 and 5.37). These correlations were also greatest at lags of zero and -1 month.

## Table 5.14

	Monthly Mean Temperature vs. Monthly Ground-Layer Leaf Presence	Monthly Mean Temperature vs. Monthly Canopy Leaf Presence	Monthly Precipitation vs. Monthly Ground- Layer Leaf Presence	Monthly Precipitation vs. Monthly Canopy Leaf Presence
Lag	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation
1	0.143	0.267	0.234	0.555
0	0.264	0.821**	0.351	0.839**
-1	0.547	0.81**	0.403	0.726*
-2	0.219	0.568	0.288	0.288

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I APPRIATIONS NOTWOOD	maan monthly tamparatily	$\alpha$ and provinitation $u$	monthly leat nrecence
	a mean monuny temperatur	C AIRT DIECHDILALIUM VS	

\*Indicates 95% Significance \*\*Indicates 99% Significance

Table 5.15 Correlations between mean monthly relative humidity and potential evaporation vs. monthly leaf presence

	Monthly Mean Relative Humidity vs. Monthly Ground-Layer Leaf Presence	Monthly Mean Relative Humidity vs. Monthly Canopy Leaf Presence	Monthly Potential Evaporation vs. Monthly Ground-Layer Leaf Presence	Monthly Potential Evaporation vs. Monthly Canopy Leaf Presence
Lag	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation
1	-0.026	0.563	0.155	0.47
0	0.485	0.854**	-0.79**	-0.697*
-1	0.88**	0.716*	-0.922**	-0.648*
-2	0.558	0.549	-0.655*	-0.563

\*Indicates 95% Significance \*\*Indicates 99% Significance

Canopy stratum leaf senescence is significantly correlated with mean monthly temperature, monthly precipitation and monthly relative humidity (Tables 5.16 and 5.17; Figures 5.38 - 5.41). These correlations were greatest at lag zero. Ground stratum leaf senescence did not produce significant associations for mean monthly temperature or monthly precipitation. Strong significant correlations were found however for mean monthly relative humidity and monthly potential evaporation (Figures 5.40 and 5.41). The significant correlations were greatest at lag -1 month.

	Monthly Mean Temperature vs. Monthly Ground-Layer Leaf Senescence	Monthly Mean Temperature vs. Monthly Canopy Leaf Senescence	Monthly Precipitation vs. Monthly Ground-Layer Leaf Senescence	Monthly Precipitation vs. Monthly Canopy Leaf Senescence
Lag	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation
1	-0.247	-0.478	-0.478	-0.656*
0	-0.264	-0.868**	-0.351	-0.857**
-1	-0.547	-0.765**	-0.415	-0.477
-2	-0.219	-0.415	-0.403	-0.253

Table 5.16 Correlations between mean monthly relative humidity and potential evaporation vs. monthly leaf senescence

Table 5.17 Correlations between mean monthly relative humidity and potential evaporation vs. monthly leaf senescence

	Monthly Mean Relative Humidity vs. Monthly Ground-Layer Leaf Senescence	Monthly Mean Relative Humidity vs. Monthly Canopy Leaf Senescence	Monthly Potential Evaporation vs. Monthly Ground-Layer Leaf Senescence	Monthly Potential Evaporation vs. Monthly Canopy Leaf Senescence
Lag	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation
1	-0.619	-0.367	0.61	-0.293
0	-0.485	-0.873**	0.79**	0.666*
-1	-0.88**	-0.543	0.922**	0.526
-2	-0.558	-0.36	0.655*	0.442

\*Indicates 95% Significance \*\*Indicates 99% Significance

### Summary:

Ground and canopy vegetation at the seasonal semi-deciduous TF site exhibited leaf flushing, presence and senescence which responded to different meteorological triggers. Ground vegetation had significant correlations with relative humidity and potential evaporation; whilst the canopy vegetation had significant associations with temperature, relative humidity and potential evaporation. The time lags (simultaneous to -1 month) were similar for both strata (Table 5.18).

These results differ substantially to those derived using litterfall (section 5.2.1). No degree of anticipation in leaf senescence or abscission is implied. Instead, the observed vegetation seems responsive to changes in the abiotic environment, specifically to changes in water status. The expansion of new leaves, and the maintenance of existing ones, requires large amounts of available water (Rundel and Becker, 1987; Borchert, 1980; Bionski and Fowler,

1989). It may be that hydroperiodic stimuli are acting to co-ordinate leaf flushing and senescence especially in the TF understorey.

Table	5.18	Comparison	of	the	meteorological	processes	and	critical	lags	in	the	leaf
pheno	phenologies of ground and canopy vegetation											

Stratum	Leaf Process	Associated Meteorological Control	Critical lag (months)	
Ground	Fluching	Relative Humidity	0/-1	
Ground	Flushing	Potential Evaporation	07-1	
	A atively <b>Bhotographesising</b>	Relative Humidity	0/1	
	Actively Photosynthesising	Potential Evaporation	07-1	
	S	Relative Humidity	1	
	Senescing	-1		
Canopy	Flushing	-	-	
		Temperature	0/1	
	Actively Photosynthesising	Precipitation	0/-1	
		Temperature		
	Senescing	Precipitation	0	
		Relative Humidity		

## 5.2.2.2 Savanna Aborizada site

Table 5.19 Direct observations of phenology at the Savanna Arborizada

			1995			1996					in Chines		
<ul> <li>phenological paramet</li> <li>phenological paramet</li> <li>no data (other phenop</li> </ul>	er absent 1 er present 2 ohase active) 3 4	leaves absent leaves emergent leaves expanded leaves senescent	September	October	November	December	January	February	March	April	May	June	
	Grass	Emergent/Expanded (2/3)	-	2	3	3	3	3	3	3	3	-	
Local Name	Pampa	Flowering	×	x	x	x	x	x	x	x	×	x	
Scientific Name	Mesosetum loliiforme	Fruiting	~	x	×	x	x	x	x	x	x	×	
Family		Senescence (1/4)	1	-	-	-	01- b	- 1	2-0	-	4	4	
	Tree 1	Emergent/Expanded (2/3)	-	2	3	3	3	3	3	3	-	-	
	Trampillo	Flowering	x	×	x	×	×	x	x	x	x	x	
	Lafoensia pacari	Fruiting	x	×	x	x	x	x	×	×	×	×	
	Lecythidaceae	Senescence	1	1	-	-	-	-	-	-	4	1	
	Tree 2	Emergent/Expanded (2/3)	2	3	3	3	3	3	3	3	3	-	
	Tinto Negro	Flowering	x	×	×	×	×	1	1	x	×	×	
	Qualea grandiflora	Fruiting	x	x	x	×	×	x	×	1	×	1	
	Vochysiaceae	Senescence (1/4)	1	-	-	-	-	-	-	-	4	1	
Cherry Bandler	Trees	Emergent/Expanded (2/3)	-	2	2	3	3	3	3	3	-	-	
		Flowering	x	~	x	x	1	x	x	x	x	×	
		Fruiting	~	~	×	x	×	×	x	×	x	×	
		Senescence (1/4)	1	-	-	-	-	-	-	-	4	1	
	Ground	Emergent/Expanded (2/3)	-	2	3	3	3	3	3	3	3	-	
		Flowering	x	x	x	x	x	~	~	~	x	x	
		Fruiting	~	×	x	x	x	x	x	x	×	~	
		Senescence (1/4)	1	-	-	-	-	-	-	-	4	4	

## Ground stratum (Figure 5.42):

The ground stratum exhibited an extremely seasonal vegetative cover which responded rapidly to the onset of the dry season (in May and June) with widespread vegetative senescence. This trend continued until the fires of late August reduced all ground vegetation to stubble (see Plate 5.2). A pronounced and rapid flush of new leaves (and indeed entire new

plants) occurred at the beginning of the wet season (October). Development of the vegetation in this stratum continued until the late wet season (April) (Plate 5.2). Antithesis was observed at the end of the wet season and seeds (fruiting) were noted throughout the dry season (June-September). Photosynthetically active leaves were present in this stratum from mid October until late May.

## Trees (Figure 5.43):

Table 5.20

The tree stratum, in the savanna, displayed less seasonality than the ground layer. Some leaf-senescence and abscission were noted during the dry season from May onwards, possibly in anticipation of a change in the seasonal availability of water (see section 5.2.1). Almost all trees retained a residual leaf cover throughout the dry season (Plate 5.1). The fire season of August and September did not have a notable affect on leaf phenology, with the majority of trees expanding their leaves early in the wet season (c. 1 month later than the ground vegetation layer). Flowering was noted during the wet season, and fruiting during the driest winter month (September). Many photosynthetically active leaves were present from October until April, although some leaves were always present.

## Associations between observations and meteorological parameters.

Since the AWS was within 0.5 kilometres, the meteorological measurements were expected to be far more representative for this verification site than those for Lomerio. However, no significant correlations could be established between canopy or ground leaf flushes and any of the meteorological parameters (Tables 5.20 and 5.21; Figures 5.44-5.47).

**Monthly Mean** Monthly Monthly **Monthly Mean Precipitation vs.** Precipitation vs. **Temperature vs. Monthly** Temperature vs. **Monthly Canopy Monthly Ground-Monthly Canopy Ground-Laver** Leaf Flush Layer Leaf Flush Leaf Flush Leaf Flush **Point Biserial Point Biserial Point Biserial Point Biserial** Lag Correlation Correlation Correlation Correlation 0.119 0.554 0.667\* 1 0.51 -0.099 0.284 -0.2470 0.131 0.284 -0.443 -0.347 0.322 -1 0.684\* -0.403 -0.555 -2 0.594

Correlations between mean monthly temperature and precipitation vs. monthly leaf flush

	Monthly Mean Relative Humidity vs. Monthly Ground-Layer Leaf Flush	Monthly Mean Relative Humidity vs. Monthly Canopy Leaf Flush	Monthly Potential Evaporation vs. Monthly Ground-Layer Leaf Flush	Monthly Potential Evaporation vs. Monthly Canopy Leaf Flush		
Lag	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation		
1	0.099	0.23	-0.127	-0.253		
0	-0.061	0	-0.202	-0.253		
-1	-0.105	-0.181 0.055		0.243		
-2	-0.691*	-0.596	0.624	0.551		

Table 5.21 Correlations between mean monthly relative humidity and potential evaporation vs. monthly leaf flush

Canopy stratum leaf presence demonstrated significant correlations with mean monthly temperature, monthly precipitation, monthly relative humidity and mean monthly potential evaporation (Tables 5.22 and 5.23; Figures 5.48 - 5.51). All correlations were greatest at lag zero (i.e. contemporaneous). Ground stratum leaf presence produced significant associations with mean monthly relative humidity (greatest at lag -1) and mean monthly potential evaporation (greatest at lag zero), Figures 5.50 and 5.51. The presence of leaves in both strata is strongly associated with the availability of water in the Savanna environment.

## Table 5.22

Correlations between mean monthly temperature and r	precipitation vs.	monthly leaf	presence
---	-------------------	--------------	----------

	Monthly Mean Temperature vs. Monthly Ground-Layer Leaf Presence	Monthly Mean Temperature vs. Monthly Canopy Leaf Presence	Monthly Precipitation vs. Monthly Ground- Layer Leaf Presence	Monthly Precipitation vs. Monthly Canopy Leaf Presence	
Lag	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation	
1	0.247	0.62	0.478	0.672*	
0	0.646*	0.782**	0.566	0.735*	
-1	0.69*	0.69* 0.68* 0.585		0.548	
-2	0.272	0.218	0.341	0.044	

	Monthly Mean Relative Humidity vs. Monthly Ground-Layer Leaf Presence	Monthly Mean Relative Humidity vs. Monthly Canopy Leaf Presence	Monthly Potential Evaporation vs. Monthly Ground-Layer Leaf Presence	Monthly Potential Evaporation vs. Monthly Canopy Leaf Presence		
Lag	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation		
1	0.619	0.667*	0.61	0.585		
0	0.682*	0.874**	-0.87**	-0.878**		
-1	0.772**	0.647*	-0.684*	-0.533		
-2	0.356	0.134	-0.38	-0.194		

Table 5.23 Correlations between mean monthly relative humidity and potential evaporation vs. monthly leaf presence

Canopy stratum and ground stratum leaf senescence produced significant correlations with all meterological parameters (Figures 5.52 - 5.55; Tables 5.24 and 5.25). All these correlations were greatest at lag zero. Leaf senescence prompted by a plant water deficit in the driest part of the austral winter is therefore hypothesised. Addicott (1978); Gong (1982); Fournier *et al.* (1986); Murphy and Lugo (1986) all note a similar relationship.

Table 5.24 Correlations between mean monthly temperature and precipitation vs. monthly leaf senescence

	Monthly Mean Temperature vs. Monthly Ground-Layer Leaf Senescence	Monthly Mean Temperature vs. Monthly Canopy Leaf Senescence	Monthly Precipitation vs. Monthly Ground-Layer Leaf Senescence	Monthly Precipitation vs. Monthly Canopy Leaf Senescence		
Lag	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation		
1	-0.62	-0.62	-0.672*	-0.672*		
0	-0.792**	-0.792**	-0.735*	-0.735*		
-1	-0.68*	-0.68*	-0.548	-0.548		
-2	-0.218	-0.218	-0.044	-0.044		

	Monthly Mean Relative Humidity vs. Monthly Ground-Layer Leaf Senescence	Monthly Mean Relative Humidity vs. Monthly Canopy Leaf Senescence	Monthly Potential Evaporation vs. Monthly Ground-Layer Leaf Senescence	Monthly Potential Evaporation vs. Monthly Canopy Leaf Senescence		
Lag	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation	Point Biserial Correlation		
1	-0.667*	-0.667*	0.585	0.585		
0	-0.874**	-0.874**	0.878**	0.878**		
-1	-0.647*	-0.647*	0.533	0.533		
-2	-0.134	-0.134	0.194	0.194		

Table 5.25 Correlations between mean monthly relative humidity and potential evaporation vs. monthly leaf senescence

## Summary:

Leaf senescence and photosynthesis both show significant correlations with meteorological variables at lag zero. The strong seasonal hydroclimate, which is typical of a savanna environment, acting to synchronise these stages of vegetative phenology (Killeen *et al.*, 1990; Lambert *et al.*, 1980; Ewel, 1976). Surprisingly, however, leaf flushing was not associated significantly with any of the meteorological variables at any lag.

Table	2.26	Comparison	of	the	meteorological	processes	and	critical	lags	in	the	leaf
pheno	logies	of ground and	l car	nopy	vegetation							

Stratum	Leaf Process	Associated Meteorological Control	Critical lag (months)	
Ground	Flushing	-	-	
	Actively Photosynthesising	Relative Humidity Potential Evaporation	0 / -1	
	Senescing	Senescing Temperature Precipitation Relative Humidity Potential Evaporation		
Canopy	Flushing	-	-	
	Actively Photosynthesising	Temperature Precipitation Relative Humidity Potential Evaporation	0	
	Senescing	Temperature Precipitation Relative Humidity Potential Evaporation	0	

# Phenological Changes at the Monitored Savanna Woodland Site, Las Trancas



FEBRARY 1996

**APRIL 1996** 

PLATE 5.2



## 5.2.2.3 Seasonally-inundated tropical forest site

Table 5.27 Direct observations of phenology at the seasonally-inundated tropical forest

			199	5		diana.	19	996				
phenological parame phenological parame no data (other pheno	eter absent 1 1 eter present 2 1 ophase active) 3 1 4 1	eaves absent eaves emergent eaves expanded eaves senescent	September	October	November	December	January	February	March	April	May	Inne
a istrict of the co	Ground 1	Emergent/Expanded (2/3)	2	2	3	3	3	2- 3	-	-		2
Local Name	Mara Marcho	Flowering	x	x	x	x	x	×	x	x	×	x
Scientific Nar	ne	Fruiting	x	x	×	×	×	×	x	x	x	3
Family	1.	Sénescence (1/4)	-	-	-		-	1- 4	1	1	1	-
-	Ground 2	EmergencExpanded (2/3)	3	3	3	3	3	3	3	3	3	
	Gesneriacae	Howering	x	x	x	x	×	x	x	x	x	3
		Fruiting	x	x	×	×	x	×	x	x	x	3
		Senescence (1/4)	-	-	-	-	-	-	-	-	-	
	Sub-Canopy 1	Emergent/Expanded (2/3)	3	3	3	3	3	3	3	3	3	
	Pachiuva	Flowering	x	x	×	x	×	×	×	×	×	1
	Iriartea venricosa	Fruiting .	x	×	×	×	x	×	x	~	~	1
	Palmae	Senescence (1/4)	-	-	-	-	-	-	-	-	-	4
	Canopy 2	Emergent/Expanded (2/3)	2	3	2	3	3	2	3	3	2	
	Charque	Flowering	×	x	x	x	×	x	x	x	x	3
	Eshweilera	Fruiting	x	x	x	x	×	x	x	x	x	1
	Lecythidaceae	Senescence (1/4)		-	-	-	-	-	-	-	-	
an a	Sub-Canopy	Emergent/Expanded (2/3)	2	3	3	3	3	3	3	3	3	
		Flowering	x	x	x	x	x	~	x	x	x	3
		Fruiting	x	x	x	x	x	x	x	x	x	-
		Senescence (1/4)	-	-	-	-	-	-	-	-	-	
	Ground	Emergent/Expanded (2/3)	3	3	3	3	3	3	3	3	3	
		Flowering	x	x	×	×	x	×	x	x	x	1
		Fruiting	×	x	x	×	x	x	x	x	x	3
		Senescence (1/4)	-	-	-	-		-	-	-	-	

#### Ground stratum (Figure 5.56):

Photosynthetically active leaves were always present in abundance in this stratum throughout the monitoring period. No general stratum-wide leaf-senescence or flushing was observed, as both processes were continuous. Flowering and fruiting were not observed.

## Sub-canopy / canopy stratum (Figure 5.57):

Again photosynthetically active leaves were ever present in great abundance and no general stratum-wide leaf senescence or flushing was observed. However, a greater amount of canopy trees renewed their leaves early in the wet season (September) and an above-average leaf senescence was noted in June. A pronounced flowering was noted in February, whilst fruiting was never visually observed (although many specimens were found in the litter traps).

## Associations between direct phenological observations and meteorological parameters

Correlation analysis could not be attempted since leaf flushing, leaf senescence and leaf presence showed insufficient seasonal variance. Medway (1972); Frankie *et al.*, (1974); Putz (1979); Boinski and Fowler (1989) all comment that leaf renewal may begin before old leaves are completely shed in humid TFs, i.e. that tropical trees may exhibit multiple phenophases. Consequently, the range of leaf phenologies will combine to create an evergreen appearance.

## Summary:

- 1. Peak annual leaf emergence was in the dry season (September) coinciding with the peak annual leaffall. Neither event significantly altered the appearance of the forest canopy.
- 2. Multiple phenophases were noted on individual plants and even on individual branches. Endogenous periodicity may therefore play an important role in the leaf phenology at Chapare. Such internal process may be synchronised by system stresses such as the dry season or inundation events.
- 3. Unfortunately, the sensitivity of my visual assessments was insufficient to determine any community-wide synchronisation. For example, the rapid leaf senescence and abscission associated with inundation (detected in litterfall, section 5.2.1) were not noted.

## **Concluding remarks:**

The leaf phenologies observed at the three verification sites were very different.

- (i) At Lomerio a seasonal semi-deciduous canopy was complimented by a more evergreen understorey. The leaf phenologies of both strata are responsive to changes in the abiotic environment.
- (ii) At Las Trancas a pronounced seasonal variance was noted in both the ground vegetation and trees. Both were highly synchronised with hyrdoclimatic periodicity.
- (iii) At Chapare all layers exhibited semi-continuous leaf flushing and senescence and showed limited signs synchronisation during the short dry season, thereby creating an evergreen appearance.

## 5.2.3 Monitoring canopy dynamics using hemispherical photography

The technique employed for analysing the hemispherical photographs acquired during this study is less complicated than most (e.g. Becker *et al.*, 1988; Chazdon and Field, 1987; Rich, 1990; Barrie *et al.*, 1990). This is because no calculation of absolute, direct or diffuse radiation was required. Rather a quantification of canopy openness (i.e. the proportion of the hemispherical projection in which the sky can be viewed) was needed. Further, since this measure of canopy openness is for comparison with remotely sensed imagery, and the latter has a maximum view angle of  $\pm 30^{\circ}$  nadir, only the central portion of the hemispherical projection is of interest. This has two distinct advantages:

- (i) the optical depth (τ) of the monitored canopy is relatively constant within these viewing geometries; and
- (ii) as a result, changes in canopy areal extent and density are easier to detect and quantify.

The manual analysis of hemispherical photographs requires the overlay of annuli (a series of concentric rings each encompassing an equal projected area) and the visual estimation of the percentage occupied by foliage and sky (Anderson, 1964a; 1964b; 1964c and Anderson, 1966a; 1966b). This process is both extremely time-consuming and prone to operator error. This study uses a five-step semi-automated method based on the methodologies of Bonhomme and Chartier (1972); Becker and Erhart (1988); Dohrenbusch (1989).

- (i) The time series of hemispherical photographs were scanned to a resolution of 800dpi using a Hewlett Packard Deskscan II Digitiser.
- (ii) Cosine-adjusted annuli of equal area were digitised from Mitchell and Whitmore (1993). The sixteen equal area annuli were then split into separate binary images, (Figures 5.58 and 5.59) (Mitchell and Whitmore, 1993).
- (iii) The digital hemispherical photographs were then registered in ERDAS IMAGINE to the annuli images (see Appendix 5.2 for RMS errors). Since the Minolta 28mm lens employed in this study samples a 110° of the hemisphere rather than the 180° of a fisheye lens, only the central 13 annuli were used (i.e. an area of 115°).
- (iv) The registered photographs were then converted to binary black and white images (grey-level thresholds being individually determined, for each date, to distinguish sky from foliage).
- (v) Using an image addition algorithm the percentage of pixels representing open sky in the seven most central annuli (i.e. 62.23° or ± 31° nadir) were then calculated.

Canopy openness data are presented in Figures 5.60, 5.62 and 5.64 (for the Lomerio, Las Trancas and Chapare verification sites respectively). Mean canopy openness of all observation positions are also plotted. Associations between mean canopy openness (%) and: (i) mean monthly dry bulb temperature; (ii) monthly precipitation; (iii) mean monthly relative humidity; and (iv) mean monthly potential evaporation were then calculated. These were lagged against the previous month's meteorological data, the previous two months meteorological data and the subsequent month's meteorological measurements. The results are shown in Figures 5.61, 5.63 and 5.65 (for the Lomerio, Las Trancas and Chapare verification sites respectively). Correlations are based on the Pearson's Product Moments and Spearman's rho (details of this method were provided in section 5.2.1, above).

## 5.2.3.1 Seasonal semi-deciduous tropical forest site

Four hemispherical photography locations were monitored at this site. These were located in diverse microenvironments in order to encompass the heterogeneity of the site (see Figure 3.5 for locations). Some initial difficulties were encountered at Point 1 since I was unable to relocate the ground location stake in September 1995. However, monitoring proceeded at *approximately* the same location. Results are plotted for each monitoring point on Figure 5.60 and Table 5.28.

	Mean	Mean	Mean	Mean	Mean
	Canopy	Canopy	Canopy	Canopy	Canopy
Date	Openness	Openness	Openness	Openness	Openness
	(%)	(%)	(%)	(%)	(%)
	Point-1	Point-a	Point-2	Point-3	Point-4
July (1995)	See Point-a	22.8	22.1	24.2	52.8
August	See Point-a	20	20	22.7	47.8
September	20.2	See Point-1	18.6	24	46.4
October	19.4	See Point-1	17.1	23.	35.1
November	18.5	8.5 See Point-1 15.3		19.8	27
December	16.4	See Point-1	15.4	19	14.6
January	16.7	See Point-1	16.2	20.3	15.2
February	19.4	See Point-1	No Data	No Data	18.6
March	No Data	See Point-1	No Data	No Data	No Data
April	22.9	See Point-1	No Data	No Data	39.3
May	25.3	See Point-1	No Data	No Data	41
June (1996)	28.6	See Point-1	No Data	No Data	No Data

Table 5.28 Canopy openness at the seasonal semi-deciduous TF

Despite some gaps in the data, a clear decline in the canopy openness is evident from the end of the dry austral winter (September) onwards. The canopy is most dense by December and then remains relatively closed and static until March-May when both foliage density and leaf area decline. The canopy is particularly dynamic at point 1 probably due the location of this point in a drier area dominated by a nearby inselberg. This acts to modify the surrounding microenvironment, which has a thin soil causing the vegetation to be particularly susceptible to seasonal water stress.

Significant correlations were noted between mean monthly temperature; precipitation; relative humidity and canopy openness. These associations were strongest at lag zero (i.e. simultaneously) and at -1 month, (Figure 5.61; Table 5.29).

These associations suggest that canopy leaf area increases to become more dense and cover a greater projected ground-area, in the hotter and wetter austral summer. At this time leaf building resources will be in abundance. This process is not instantaneous, the negative lag of one month indicating that canopy leaf expansion may take up to a month to reach full capacity. Canopy reductions in openness (i.e. becoming thinner and more localised) are associated with the drier austral winter when litterfall and leaffall are initiated to reduce evapotranspirational losses (Addicot, 1978: Borchert, 1994a). These results are in general agreement with those of the canopy phenological observations reported earlier (section 5.2.2).

Lag	Mean Monthly Temperature	Monthly Precipitation	Mean Monthly Relative Humidity	Mean Monthly Evaporation
1	-0.693*	-0.43	-0.325*	0.298
0	-0.803**	-0.829**	-0.627*	0.506
-1	-0.836**	-0.845**	-0.728*	0.554
-2	-0.523	-0.688*	-0.718*	0.635*

Table 5.29 Correlations between meteorological parameters and canopy openness

\*Indicates 95% Significance \*\*Indicates 99% Significance

#### 5.2.3.2 Savanna Aborizada site

The tree monitored at this site exhibited a clear and dramatic change in canopy openness (Figure 5.62; Table 5.30). The start of the wet austral summer (October) was associated with a pronounced reduction in canopy openness. The tree then remained in full leaf until March-April when a gradual decline in crown density and leaf area began to occur.

	Canopy
Date	Openness
	(%)
July	80
August	83
September	76.8
October	27
November	37
December	26
January	29
February	26
March	48
April	62
May	59
June	57

Table 5.30 Canopy openness at Las Trancas

Significant correlations were noted between all meteorological variables and canopy openness. Relative humidity and evaporation demonstrated the strongest associations. These were strongest at a lag of zero (i.e. changes in humidity and potential evaporation were associated with contemporaneous changes in canopy openness) (Figure 5.63; Table 5.31). Canopy development is then well synchronised with climatic hydro-periodicity (Brunig, 1983; Alvim and Alvim, 1978; Wieder and Wright, 1995).

Lag	Mean Monthly Temperature	Monthly Precipitation	Mean Monthly Relative Humidity	Mean Monthly Evaporation
1	-0.789**	-0.791**	-0.684*	0.551
0	-0.724**	-0.697*	-0.841**	0.82*
-1	-0.694*	-0.532	-0.64*	0.633*
-2	-0.395	-0.4	-0.084	0.111

Table 5.31 Correlations between meteorological parameters and canopy openness

\*Indicates 95% Significance \*\*Indicates 99% Significance

#### 5.2.3.3 Seasonally-inundated tropical forest

Canopy openness showed no overall seasonal trends at the three locations monitored at Chapare (Figure 5.64; Table 5.32). Some seasonal variation was evident at Point 2, where a decline in canopy openness was detected in September. The other two monitoring points produced conflicting data for this period. A slight reduction in canopy density and areal extent at all four points in February is noteworthy since it may be associated with wet season leaffall (section 5.2 above).

Table 5.52 Derived canopy openness at Chapare				
	Mean	Mean	- Mean	
	Canopy	Canopy	Canopy	
Date	Openness	Openness	Openness	
	(%)	(%)	(%)	
	Point-1	Point-2	Point-3	
August (1995)	34.9	32.6	21	
September	32.6	19.7	28.3	
October	38.4	24.8	26.4	
November	29	36.2	30.7	
December	34.1	31.4	27.1	
January	37.4	32.7	29	
February	40.5	35	31.1	
March	32.9	29.4	26.2	
April	37.6	27.4	26.5	
May	35.7	28.3	23.1	
June (1996)	No Data	No Data	No Data	

Table 5.32 Derived canopy openness at Chapare

Only one significant association was evident, that between canopy openness and monthly total precipitation at lag-1, (Figure 5.65; Table 5.33).

Table 5.33 Correlations between meteorological parameters and canopy openness

Lag	Mean Monthly Temperature	Monthly Precipitation	Mean Monthly Relative Humidity	Mean Monthly Evaporation
1	0.29	0.387	0.269	0.286
0	0.544	0.498	0.441	-0.018
-1	0.576	0.79*	0.327	0.366
-2	0.113	0.014	-0.168	0.127

\*Indicates 95% Significance \*\*Indicates 99% Significance

## **Concluding remarks:**

Many problems were encountered during the acquisition and analysis of the hemispherical photographs for this study. The most notable being the following:

- (i) Camera mis-orientation and positioning. This led to unexpectedly high RMS errors when registering the time series of photographs. This process was further complicated by the sometimes rapid canopy change and lack of non-ephemeral tie points.
- (ii) At the Savanna Aborizada ground verification site, the canopy was very near to the lens (due to the lower tree heights). This led to large levels of distortion and associated registration problems. In such conditions the use of normal projection photography for monitoring changes in vegetation may be quicker, less complicated and as effective.
- (iii) Under and overexposure of film. This was especially problematic given the photos were taken near to solar noon.

(iv) The manual selection of grey level thresholds was subjective. Chazdon and Field (1987) note that this may cause large gaps to be over represented and small gaps under represented.

At the seasonal semi-deciduous TF and Savanna Aborizada sites, a clear trend in canopy openness was noted. During the more humid summer wet season canopy openness decreased; whilst during the winter drier season openness increased. These changes in canopy density and leaf area are highly correlated with changes in meteorological conditions, especially hydroclimatic parameters. No seasonal trends in canopy openness or associations with meteorological parameters emerged at the seasonally-inundated TF site.

## 5.2.4 Monitoring canopy dynamics using a Ceptometer

Ceptometer transects were walked at the semi-deciduous TF and seasonally-inundated TF sites on a monthly 'as and when possible' basis according to the criterion:

- (i) Sunfleck and Photosynthetically Active Radiation (PAR) measurements were acquired when:
  - (a) the sun was not obscured (i.e. cloudless sky); and
  - (b) local solar time was +/-2.5 hours from local solar noon.

Acquiring data under these circumstances ensured that the sun approximated a point source (in fact it subtends an angle of 0.5 degrees; Anderson, 1964a) and that the optical depth of canopy ( $\tau$ ) attenuating direct EMR was almost constant. Both of these conditions are necessary assumptions for the inversion of sunfleck data.

(ii) If either of the above conditions were not met, only PAR measurements were recorded.

## Using PAR to determine LAI

PAR measured beneath a canopy is a combination of both radiation transmitted through it and radiation scattered by the leaves within the canopy.  $\tau$ , the ratio of un-attenuated PAR (in the open) to that beneath the canopy, can be used to infer canopy LAI. Numerous models seek to explain this relationship, one of the most notable being that of Goudriaan (1988). Here the fraction of transmitted PAR ( $\tau$ ) is defined as:

$$\tau = f_b \exp(-\sqrt{aKL}) + 1 - f_b \exp(-0.87\sqrt{aL})$$
 [5.1]

Where:

L is LAI;

 $f_b$  is the fraction of incident PAR which is direct (beam radiation);

a is the leaf absorbivity (of  $PAR_{\lambda}$ ) typically around 0.9; and

K is the extinction coefficient for the canopy.

If LAD is assumed spherical, K may be defined as:

$$K = \frac{1}{2\cos\theta}$$
<sup>[5.2]</sup>

Where:

 $\theta$  is the solar zenith angle at the time of data acquisition.

See appendix 2.3 (for calculations of the Equation of Time).

Norman and Campbell (1989) describe a more easily inverted model where  $\tau$  is defined as:

$$\tau = \exp\left\{\frac{A(1 - 0.47f_b)L}{\left(1 - \frac{1}{2K}\right)f_b - 1}\right\}$$
[5.3]

Where:

 $A = 0.283 + 0.785a - 0.159a^2$ 

Assuming a=0.9 and  $f_b = 0$ , A= 0.86

By inverting Eq. 5.3 LAI can be obtained from:

$$L = \frac{\left[ \left( 1 - \frac{1}{2K} \right) f_b - 1 \right] \ln \tau}{A(1 - 0.47 f_b)}$$
[5.4]

After collecting and compiling this data this author was advised (personal communication Matt Johnson, Decagon Devices, Inc., 1998) that inversion using transmitted PAR is far more accurate in tall and / or small-leaved canopies than by sunfleck inversion due to the effects of penumbrae (areas neither in full shade or shadow). PAR inversions have the further advantage that LAI estimations for all months (cloudy or clear) can be obtained.

The correlations between derived leaf area (for both sites) and: (i) mean monthly dry bulb temperature; (ii) monthly precipitation; (iii) mean monthly relative humidity, and (iv) mean monthly potential evaporation were then calculated using Pearson's Product Moment Correlation and Spearman's rho (for data with the following monthly lag: -2, -1, 0 and +1), in a manner similar to that described in section 5.2.1 above, (Figure 5.67).

Ceptometer data were acquired from two transects walked monthly at the Lomerio site, and three base-line inventory transects walked monthly at the Chapare site. Measurements from these transects were then combined and plotted (Figure 5.66 which compares the mean derived LAI, for Lomerio and Chapare). Both sites show clear and distinct seasonal canopy leaf area changes.

1

Derived canopy leaf area at the semi-deciduous TF site varies in a sinusoidal manner (Figure 5.66; Table 5.34). Increases in LAI are evident from September onwards (the end of the dry austral winter) and become particularly rapid in October and November. Maximum canopy density is attained at, or around, the austral summer solstice after which canopy leaf area declines steadily to its dry season levels. At the seasonally-inundated TF (Table 5.35), the derived canopy leaf area displays less seasonal variation. An increase in LAI at the beginning of the austral summer is evident but the canopy never becomes as dense as those at Lomerio. By February, canopy LAI has declined slightly and then remains static for the remainder of the study.

( denotes cloudy PAR inversion)				
Transect	Derived LAI	Derived LAI		
Date	Transect 1	Transect 2		
July	5.2	5.4		
August	5.3	5.3		
September	5.6	5.7		
October	5.4	6.6		
November	8.7*	7.9*		
December	9.1*	8.1*		
January	8.3*	8.7*		
February	8.9*	7.9*		
March	7.3	6.7		
April	6.2	6.1		
May	6	5.8		
June	5.9	5.6		

Table 5.34 Derived canopy LAI at Lomerio (\* denotes cloudy PAR inversion)

Table 5.35 Derived	canopy LAI at Chapare
(* denotes clou	dy PAR inversion)

( denotes croud) i rinchionon)				
	Derived	Derived	Derived	
Transect	LAI	LAI	LAI	
Date	Linear	Linear	Linear	
	Madre1	Madre2	Madre3	
August	6.4	6.4	6.2	
September	6.2	6.4	6.6	
October	7.3	7.2	7.3	
November	9.6*	8.6*	7.6*	
December	7.2	7.3	7.4	
January	9.1*	8.3*	7*	
February	8.2*	8.1*	7.9*	
March	6.2	6.3	7.1	
April	7.4	6.7	7.2	
May	7.3	7	7.4	
June	7	6.9	7.2	
Significant correlations were noted between all meteorological variables and derived LAI at the semi-deciduous TF site. These associations are generally strongest at lag-zero, Figure 5.67; Table 5.36. Meteorological variables with a hydrological component (i.e. precipitation, relative humidity and evaporation) again demonstrate the strongest associations (Figure 5.68).

Table 5.36	Correlations	between	meteorological	variables	and	derived	canopy	LAI	at	the
Seasonal sen	ni-deciduous	ΓF	_							

Lag	Mean Monthly Temperature	Monthly Precipitation	Mean Monthly Relative Humidity	Mean Monthly Evaporation
1	0.723*	0.55	0.634	-0.514
0	0.676	0.866**	0.904**	-0.847**
-1	0.503	0.719*	0.588	-0.562
-2	-0.47	0.203	0.107	-0.172
	+1.1	050/ 01 10	*** 1' ( 000	<u> </u>

\*Indicates 95% Significance \*\*Indicates 99% Significance

The semi-deciduous nature of the canopy trees at Lomerio is once again apparent. Although LAI never falls below 5, this strata is clearly sensitive to hydrological changes, derived LAI increasing and decreasing simultaneously with the meteorological variables. The mechanism for such a quick response to abiotic triggers is unclear. Killeen *et al.* (1990) term such leaf phenologies 'facultatively deciduous' and Adis *et al.* (1979) comment that only with trees with large stem storage capacities can fund such responsive phenologies.

At the seasonally-inundated TF site only one significant linear association was evident. This was between Ceptometer-derived LAI and contemporaneous mean monthly temperature (Table 5.37). No logical physiological-phenology process links these two variables however and the association is thought spurious.

Lag	Mean Monthly Temperature	Monthly Precipitation	Mean Monthly Relative Humidity	Mean Monthly Evaporation
1	0.34	011	0.403	0.226
0	0.788*	0.224	0.437	0.302
-1	0.667	0.365	0.679	-0.047
-2	0.123	0.15	-0.241	-0.522

Table 5.37 Correlations between meteorological variables and derived canopy LAI at the Seasonally-inundated TF

\*Indicates 95% Significance \*\*Indicates 99% Significance

#### Summary:

1

1. Model inversion using ratios of un-attenuated to canopy-perturbed PAR have produced credible, if crude, estimations of canopy leaf area.

- 2. It should be noted however, that there is some uncertainty involved in the inversion process. When inverting from cloudy month's data f<sub>b</sub> was assumed to be 0 (i.e. no direct beam radiation is present) and the canopy structural information (K) was not calculated. The result of this is an inversion that produces a slightly higher estimate of L for these months. Unfortunately, cloudy data inversions coincide with periods where maximum LAI would be expected to occur. (See Appendix 5.2.4.b).
- 3. Although not perfect, the PAR inversions produced more credible estimations than sunfleck inversions. Here potential sources of error, such as the affects of penumbra and slight diurnal variations in solar zenith (a function of the +/- 2.5 hours solar noon sampling time) introduced large error terms.

Both the seasonal semi-deciduous TF and the seasonally-inundated TF demonstrated seasonal changes in derived leaf area. These were greater at the more seasonal semi-deciduous TF site and highly significant correlations were established between all meteorological parameters and changes in leaf area.

# 5.2.5 Monitoring the reflectance of ground, understorey and tree mosaics using an automated radiometry system

Automated reflectance measurements were recorded daily at 10:15 and 14:15 at two simulated AVHRR wavelengths at the three field sites. The AVHRR Channel 1 (0.58 - 0.68 nm) was approximated in two ways using a photodiode (with a spectral response of 350 - 1,050 nm with a peak at 800 nm). Output-1 has a spectral response of 600 nm to 1,050 nm with a peak at 800 nm and Output-2 is a function of spectral response of 600 - 800 nm with a peak at 800 nm (section 3.4.5). AVHRR Channel 2 (735-1,100 nm) was simulated using a photodiode with a spectral response of 800-1,050 nm with a peak at 920 nm.

Each of these three output voltages were then converted to a standardised reflectance factor:

$$\rho_{\lambda} = \left[\frac{V \uparrow_{1}}{V \downarrow_{n} - D \downarrow_{n}}\right] x 100$$
<sup>[5.5]</sup>

#### Where:

 $V\uparrow_1$  = voltage for an upward-looking photodiode;

 $V \downarrow_n$  = voltage for an downward-looking photodiode;

 $D\downarrow_n$  = Calibration coefficient for the downward-looking photodiode;

 $\rho_{\lambda}$  = standardised reflectance factor (%), i.e. the ratio of irradiance reaching the upward looking photodiode simultaneously reflected by the target vegetation mosaic (recorded by the downward-looking photodiode).

This standardised reflection factor (for each downward-looking diode) is then a function of the target area beneath it (reflecting EMR) and the leaf area above it (that will have acted to attenuate the incident irradiance).

$$\rho_{\lambda} = f(\rho_{LAI}^{below} \tau_{LAI}^{above})$$
<sup>[5.6]</sup>

#### Where:

 $\rho_{\lambda}$  is the standardised reflectance of the downward looking diode;

 $\rho_{\text{LAI}}$  the reflection from the target vegetation mosaic beneath the diode (a function of phenology); and

 $\tau_{\text{LAI}}$  the attenuation of the incident irradiance by the thickness of (sub)-canopy above the target vegetation mosaic. This is also a function of phenology.

A significant problem remains. This study aims to understand the phenological changes that occur in TF vegetation. However, within these radiometric measurements two parameters are in flux:

- (i) the illumination conditions (both in terms of the absolute amount of EMR incident on the TF and in terms of its direct and diffuse components); and
- (ii) the monitored vegetation target.

Since both the absolute and relative values of  $\rho_{LAI}$  and  $\tau_{LAI}$  will be different for diffuse and direct sunlight (Evans, 1956; Anderson, 1964a; Anderson, 1966b; Ross, 1981; Pinker, 1982; Norman and Campbell, 1989; Gilabert and Melia, 1993) the illumination conditions must be standardised. Tooming and Niilisk (1967) suggest empirically derived direct/diffuse light conversion factors based on solar elevation. Perelyot (1970) developed conversion factors using measures of atmospheric transparency (n-cloud numbers). However, the purpose of this radiometry system is to acquire reflectance measurements contemporaneously with specific satellite image acquisitions. Since optical remote sensing (i.e. that below 1.1 µm) can only be successfully completed in cloud-free (or near-cloud-free) conditions, the remotely sensed images themselves have the screening characteristics necessary to standardise the illumination conditions. Therefore, only ARS measurement (14:15) dates with corresponding AVHRR cloud-free images were selected for analysis. Unfortunately, insufficient ATSR-2 image dates were available to temporally filter the 10:15 readings. The flagged (useful) and unflagged (cloudy) upward-looking diode voltages were then plotted against the AWS 14:00 hrs solarimeter readings (Figure 5.68). The result is an almost linear association between the two measures of irradiance (r= 0.87; 95% confidence). A semi-constant total EMR flux and diffuse : direct flux ratio is assumed for each of the flagged ARS measurements. This ratio has been calculated as approximately 10:90 (diffuse : direct) by Anderson (1964a) for clear cloudless skies at local solar noon.

Two normalised difference vegetation indices, for each target mosaic area, were then derived, using the two approximations of AVHRR Channel-1:

$$\rho_{NDVI^{1}} = \frac{\left(\rho_{Channel\,2} - \rho_{Output\,1}\right)}{\left(\rho_{Channel\,2} + \rho_{Output\,1}\right)}$$

$$= 159 -$$
[5.7]

Where:

 $\rho_{Channel2}$  is the standardised reflectance factor for Channel2  $\rho_{Output1}$  is the standardised reflectance factor for Channel1 (Output1)  $\rho_{NDVI}^{1}$  is the NDVI (using the first AVHRR Channel 1 approximation). And,

$$\rho_{NDVI^{2}} = \frac{\left(\rho_{Channel\,2} - \rho_{Output\,2}\right)}{\left(\rho_{Channel\,2} + \rho_{Output\,2}\right)}$$
[5.8]

#### Where:

 $\rho_{\text{Channel2}}$  is the standardised reflectance factor for Channel2  $\rho_{\text{Output2}}$  is the standardised reflectance factor for Channel1 (Output2)  $\rho_{\text{NDVI}}^2$  is the NDVI (using the second AVHRR Channel 1 approximation).

For the purposes of this discussion, it is useful to interpret the ARS-NDVI data in terms of the different reflective components within the ARS-FOV. Three distinct and different spatial mosaics were monitored at each site.

- (i) A Ground Mosaic (<1 m), monitored by one diode-pair at each site, consisting of leaf litter; soil (the reflectance of which will vary mainly as a function of water content) and various forms of grass, sedge and juvenile vegetation which are site specific. The vegetation-sensor distance was not constant but only at one site (the Savanna Aborizada) is it thought to have affected the size of the FOV.
- (ii) An Understorey-1 (c. 5m) mosaic (monitored by two diode-pairs at the Lomerio and Chapare, and one pair at Las Trancas). This FOV consisted of canopy tree boles, with large spaces between woody components containing understorey vegetation and forest floor components.
- (iii) An Understorey-2 mosaic. As above, but at < 15m.

At Las Trancas (Savanna Aborizada verification site) the diode-pair was placed c. 1m above the canopy of a *Curatella americana* (Savanna tree), Plate 3.12.

The differences in ARS-NDVI within and between ground verification sites were then tested using a one-way analysis of variance (ANOVA). The null hypothesis was that all samples came from the same group. The ANOVA F statistic is an analysis of the variance

between groups divided by the variance within groups. A high value of F rejects the hypothesis, a low F supports it.

Between site variance was tested by comparing: (i) all reflectance measurements from each site; (ii) the reflectance measurements from each strata independently. (iii) Variance between the strata at each site were then tested.

	F	Level at which Significant (%)
Verification Sites Compared	2 400	
All Measurements (Output-1)	2.409	90
Verification Sites Compared	3.126	00
Ground Measurements (Output-1)	5.120	90
Verification Sites Compared	0.458	
U-1 Measurements (Output-1)	0.450	
Verification Sites Compared	0.813	_
U-2 Measurements (Output-1)	0.015	
Lomerio vs. Las Trancas	4.68	95
All Measurements (Output-1)		
Lomerio vs. Las Trancas	6.912	99
Ground Measurements (Output-1)		
Lomerio vs. Las Trancas	4.129	99
U-1 Measurements (Output-1)		
Lomerio vs. Las Trancas	3.172	95
U-2 Measurements (Output-1)	1.724	
Lomerio Strata Compared (Output-1)	1./34	<u>95</u>
Las Trancas Strata Compared (Output-1)	2.05	99
Chapare Strata Compared (Output-1)	0.81	
All Measurements (Output 2)	3.262	-
All Measurements (Output-2)		<b> </b>
Verification Sites Compared	4.392	-
Ground Measurements (Output-2)		
Verification Sites Compared	0.347	-
Varification Sites Compared		
Verification Sites Compared	0.411	-
U-2 Measurements (Output-2)		
Lomerio vs. Las Trancas	1.63	-
An Measurements (Output-2)		<u> </u>
Lomerio VS. Las Trancas Cround Mossuroments (Output 2)	1.984	90
Lomerio vs. Las Tranças		
U-1 Measurements (Output-2)	0.684	-
Lomerio vs. Las Tranças		
Lonicho vs. Las Haircas LL-2 Measurements (Outnut-2)	0.646	-
Lomerio Strata Compared (Output-2)	0.93	
Las Tranças Strata Compared (Output-2)	0.172	-
Chapare Strata Compared (Output-2)	0.386	
Chapare Suata Compared (Output-2)	0.500	L

Table 5.38 Comparisons of ARS-NDVI variance between verification site and between strata (one-way, ANOVA) both output options

Between site variation in the ARS-NDVI measurements was minimal. Only the Output-1 results rejected the hypothesis that the measurements from the three verification sites could all have originated from the same population (at the 90% confidence level). However, when the - 161 -

semi-deciduous TF and savanna Aborizada verification sites were compared independently a significantly higher variance (at 95-99% confidence) at the site-wide and per-strata levels was obtained (Table 5.38). Between strata (ARS-NDVI) variance was significant at Lomerio (at 95% confidence level) and Las Trancas (99% confidence level) but not at Chapare.

The mean ARS-NDVI for each stratum's mosaic are shown in Figures 5.69, 5.75 and 5.81. Output-1 measurements were used since they had a higher between group variance. Monthly Maximum Value Composites (MVC) and mean-Value Composites (mean-VC) were then plotted for each site, Figures 5.70, 5.76 and 5.82 (see section 4.2 for details of the methodology). Using the same correlation and regression techniques described in 5.2.1, changes in ARS-NDVI for each strata-mosaic were then compared to meteorological changes at the nearest AWS, Figures 5.71 - 74; 5.77 - 5.80; 5.83 - 5.86.

#### 5.2.5.1 Seasonal semi-deciduous tropical forest site

The ground reflectance mosaic at Lomerio exhibited a pronounced seasonal change in its normalised difference reflectance (Figures 5.69 and 5.70). ARS-NDVI was highest (0.4-0.5) in the wetter austral summer months and lowest (0.1-0.2) in the drier austral winter. Withinstrata variance was highest during the dry season, although this is probably due to the greater number of measurements during this period.

The understorey reflectance mosaics were far less seasonally variable. The only significant trend was a decline in the lower understorey ARS-NDVI from April onwards (i.e. at the start of the dry season).

Very high, significant correlations were obtained between the ground monitoring ARS-NDVI and contemporaneous monthly precipitation, mean monthly relative humidity and mean monthly evaporation (Tables 5.39 - 55.42; Figures 5.71 - 5.74). This indicates the response of the ground stratum to changes these meteorological conditions is rapid. Abiotic triggers, particularly those with a hydrological component seem to be important. The location of the ground observing diode-pair may give some clue to these results. The site is an open clearing characterised by a dry microclimate with the deciduous trees (*Spondias mombin* and *Chorisia speciosa*) being well represented.

	Monthly Mean Temperature vs. Mean Monthly Normalised Reflectance Factor Ground		Monthly Mean Temperature vs. Mean Monthly Normalised Reflectance Factor Understorey-1		Monthly Mean Temperature vs. Mean Monthly Normalised Reflectance Factor Understorey-2	
Lag	Pearson's	Spearman's rho	Pearson's	Spearman's Rho	Pearson's	Spearman's rho
1	0.552	0.595*	0.407	0.392	0.38	0.286
0	0.686*	0.788**	0.436	0.325	0.597*	0.64*
-1	0.552	0.595*	0.407	0.392	0.38	0.286
-2	0.056	0.077	0.472	0.519	0.266	0.244

## Table 5.39 Correlations between ARS measurements and mean monthly temperature

\*Indicates 95% Significance \*\*Indicates 99% Significance

# Table 5.40 Correlations between ARS measurements and monthly precipitation

	Monthly Precipitation vs. Mean Monthly Normalised Reflectance Factor Ground		Monthly Precipitation vs. Mean Monthly Normalised Reflectance Factor Understorey-1		Monthly Precipitation vs. Mean Monthly Normalised Reflectance Factor Understorey-2	
Lag	Pearson's	Spearman's rho	Pearson's	Spearman's Rho	Pearson's	Spearman's rho
1	0.621*	0.644*	0.347	0.345	0.435	0.504
0	0.826**	0.916**	0.455	0.117	0.428	0.506
-1	0.621*	0.644*	0.347	0.345	0.435	0.504
-2	0.273	0.249	0.42	0.609*	0.501	0.379

\*Indicates 95% Significance \*\*Indicates 99% Significance

### Table 5.41 Correlations between ARS measurements and mean relative humidity

	Monthly Mean Relative Humidity vs. Mean Monthly Normalised Reflectance Factor Ground		Monthly Mean Relative Humidity vs. Mean Monthly Normalised Reflectance Factor Understorey-1		Monthly Mean Relative Humidity vs. Mean Monthly Normalised Reflectance Factor Understorey-2	
Lag	Pearson's	Spearman's rho	Pearson's	Spearman's rho	Pearson's	Spearman's rho
1	0.661*	0.799**	0.256	0.416	0.679*	0.654*
0	0.959**	0.926**	0.062	0.085	0.479	0.478
-1	0.661*	0.799**	0.256	0.416	0.679*	0.654*
-2	0.217	0.498	0.497	0.599*	0.511	0.544

\*Indicates 95% Significance \*\*Indicates 99% Significance

	Monthly Mean Evaporation vs. Mean Monthly Normalised Reflectance Factor Ground		Monthly Mean Evaporation vs. Mean Monthly Normalised Reflectance Factor Understorey-1		Monthly Mean Evaporation vs. Mean Monthly Normalised Reflectance Factor Understorey-2	
Lag	Pearson's	Spearman's rho	Pearson's	Spearman's rho	Pearson's	Spearman's rho
1	-0.555	-0.627*	-0.102	-0.304	-0.65*	-0.572
0	-0.918**	-0.9*	-0.1	-0.23	-0.479	-0.488
-1	-0.555	-0.627*	-0.102	-0.304	-0.65*	-0.572
-2	-0.159	-0.245	-0.325	-0.484	-0.382	-0.375

Table 5.42 Correlations between ARS measurements and mean monthly evaporation

\*Indicates 95% Significance \*\*Indicates 99% Significance

The rapid changes in ARS-NDVI in this layer are likely to have been caused not just by leaf-flushing, senescence and abscission of established vegetation but also by seasonal changes in the total biomass. Two plant physiological explanations are therefore necessary.

The first scenario considers an established plant, the architecture of which already exists. Leaves are exchanged (renewed) in October and November as the increased water availability of the summer allows a flush. After renewal red reflectance will decline since the new leaves will be photosynthetically efficient in their absorption of PAR (in the visible wavelengths) and their total number (LAI) will have increased. Changes in near infrared reflectance will be less pronounced, however, since the existing vegetation architecture (and old leaves) will have been reflecting EMR at these wavelengths all year round. On senescence these leaves will again primarily effect red reflectance.

Scenario two, considers smaller, annual vegetation. When leaf flush occurs a plant architecture is created as well as photosynthetic pigmentation. This will affect a change in the reflection of both red and near infrared wavelengths.

However, coupled with the above is the affect of leaf area asymptote. At LAI > 3-4 (in the red wavelengths) and LAI > 8-9 (in the near infrared wavelengths) no further increases in reflectance are detectable (Goel, 1988). The result is that the red wavelengths are much less sensitive to changes in leaf area than are the near infrared wavelengths. The overall effect is that a new flush of vegetation or the greening of a bare stratum provokes a much more profound change in ARS-NDVI than leaf exchange (which may be hard to detect spectrally above the visible LAI asymptote). This goes some way towards explaining the lack of variance in the diode pairs monitoring the understorey.

However, another explanation is possible. The canopy will have attenuated PAR (visible wavelengths) and relatively enriched the NIR wavelengths. As a result, exaggeration of the

understorey ARS-NDVI values may occur when the canopy is at its most dense (maximum  $\tau$ ). Under estimations of ARS-NDVI will occur during periods of minimum canopy leaf area (minimum  $\tau$ ). If the understorey vegetation utilises the open canopy season to flush their leaves a problem arises. The canopy and understorey phenophases could cancel each other out, i.e. as LAI in the canopy rises, an increased amount of visible radiation is absorbed and NIR scattered just as reductions in leaf area in the understorey result in less visible absorption and NIR reflectance. These two opposed phenological stages combined could produce an evergreen spectral response.

In summary, a clear phenology emerged for the ground stratum. This was highly correlated with meteorological parameters. Interpretation of the understorey reflectance is however ambiguous.

#### 5.3.1.2 Savanna Aborizada site

Seasonal changes in ARS-NDVI measurements are synchronised and follow a nearsinusoidal vector at this site (Figures 5.75 and 5.76). The Ground-1 mosaic generally displays lower ARS-NDVI values than the higher strata, possibly due to the increased influence of the highly reflective savanna soil in this reflectance mosaic. All strata begin with low ARS-NDVI values in the austral winter (August) attaining their maximum ARS-NDVI values during the austral winter.

	Monthly Mean Temperature vs. Mean Monthly Normalised Reflectance Factor Ground-1		Monthly Mean Mean Month Reflectar Grou	Temperature vs. ly Normalised ice Factor ind-2	Monthly Mean 7 Mean Monthl Reflectan Tr	Femperature vs. y Normalised ce Factor ee
Lag	Pearson's	Spearman's rho	Pearson's	Spearman's rho	Pearson's	Spearman's rho
1	0.567	0.532	0.437	0.378	0.47	0.476
0	0.758**	0.785**	0.708**	0.699*	0.771**	0.755**
-1	0.882**	0.928**	0.855**	0.895**	0.885**	0.86**
-2	0.694*	0.725**	0.755**	0.769**	0.73**	0.797**

Table 5.43 Correlations between ARS measurements and mean monthly temperature

\*Indicates 95% Significance \*\*Indicates 99% Significance

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	Monthly Precipitation vs. Mean Monthly Normalised Reflectance Factor Ground-1		Monthly Precipitation vs. Mean Monthly Normalised Reflectance Factor Ground-2		Monthly Precipitation vs. Mean Monthly Normalised Reflectance Factor Tree	
Lag	Pearson's	Spearman's rho	Pearson's	Spearman's rho	Pearson's	Spearman's rho
1	0.677*	0.66*	0.592*	0.585*	0.655*	0.616*
0	0.858**	0.905**	0.812**	0.83**	0.849**	0.858**
-1	0.766*	0.874**	0.784**	0.865**	0.787*	0.869**
-2	0.522	0.635*	0.646*	0.718**	0.636*	0.722**

## Table 5.44 Correlations between ARS measurements and monthly precipitation

\*Indicates 95% Significance \*\*Indicates 99% Significance

## Table 5.45 Correlations between ARS measurements and mean monthly relative humidity

	Monthly Mean Relative Humidity vs. Mean Monthly Normalised Reflectance Factor Ground-1		Monthly Mean Relative Humidity vs.Monthly Mean Relative Humidity vs.Mean Monthly Normalised Reflectance Factor Ground-1Mean Monthly Normalised Reflectance Factor Ground-2		Monthly Mean Relative Humidity vs. Mean Monthly Normalised Reflectance Factor Tree	
Lag	Pearson's	Spearman's rho	Pearson's	Spearman's rho	Pearson's	Spearman's rho
1	0.762**	0.852**	0.746**	0.784**	0.707*	0.808**
0	0.926**	0.926**	0.934**	0.9**	0.886**	0.956**
-1	0.74**	0.768**	0.742**	0.794**	0.816**	0.815**
-2	0.405	0.463	0.426	0.555	0.5	0.503

\*Indicates 95% Significance \*\*Indicates 99% Significance

Table 5.46 Correlations between ARS measurements and mean monthly evaporation

	Monthly Mean Evaporation vs. Mean Monthly Normalised Reflectance Factor Ground-1		Monthly Mean Evaporation vs. Mean Monthly Normalised Reflectance Factor Ground-2		Monthly Mean Evaporation vs. Mean Monthly Normalised Reflectance Factor Tree	
Lag	Pearson's	Spearman's rho	Pearson's	Spearman's rho	Pearson's	Spearman's rho
1	-0.661*	-0.648*	-0.686*	-0.615*	-0.617*	-0.594*
0	-0.88**	-0.907**	-0.88**	-0.825**	-0.817**	-0.853**
-1	-0.691*	-0.834**	-0.679*	-0.79**	-0.753**	-0.874**
-2	-0.352	-0.602*	-0.341	-0.734**	-0.453	-0.65*

\*Indicates 95% Significance \*\*Indicates 99% Significance

For all diode-pairs highly significant correlations were obtained with temperature (at a lag of -1) and with precipitation, relative humidity and potential evaporation at a lag of zero (Tables 5.43 - 5.46; Figures 5.77 - 5.79). All vegetative components in the savanna seem to respond rapidly to the changing abiotic environment. Changes in ARS-NDVI result primarily from biomass accumulation in the ground layer and changes in LAI in the tree layer. Starting in the austral summer, the ground is almost bare and the red and near infrared wavelengths will be dominated by soil reflectance. As the savanna ground vegetation forms (as a response to the increased water availability in the summer months) visible reflectance decreases (due to chlorophyll absorption and increased shadowing), while near infrared reflectance increases. ARS-NDVI continues to rise until the ground vegetation has reached its maximum areal extent and highest density in February. Subsequently, the ARS-NDVI declines. This process is more gradual, however, since reflectances in the near infrared continue to be high, as vegetation structural features remain, until the plant biomass is destroyed by burning late in the dry season.

#### 5.3.1.3 Seasonally-inundated tropical forest site

Seasonal variations in the ARS-NDVI values at the seasonally-inundated TF were very low. Monthly composites of the ground and understorey reflectance mosaics (Figures 5.81 and 5.82) do however show steady increases in ARS-NDVI until December. All reflectance mosaics show a marked decline during May and June 1996.

The seasonal variance detected in the ground reflectance mosaic may be explained by small increases in leaf area expansion from July to December or by leaf exchanges and subsequent improvements in PAR absorption. The only significant correlations were those between contemporaneous precipitation and the subsequent month's rainfall. Neither of these explain any physiological changes since water is unlikely to be a limiting factor in this environment.

	Monthly Mean Temperature vs. Mean Monthly Normalised Reflectance Factor Ground	Monthly Mean Temperature vs. Mean Monthly Normalised Reflectance Factor Understorey-1	Monthly Mean Temperature vs. Mean Monthly Normalised Reflectance Factor Understorey-2
Lag	Spearman's Rho	Spearman's Rho	Spearman's Rho
1	0.543	0.098	-0.104
0	0.494	-0.11	-0.47
-1	0.329	0.018	-0.006
-2	0.231	0.604	0.579

Table 5.47 Correlations between ARS measurements and mean monthly temperature

\*Indicates 95% Significance \*\*Indicates 99% Significance

**CHAPTER 5, Ground Verification Results** 

	Monthly Precipitation vs. Mean Monthly Normalised Reflectance Factor Ground	Monthly Precipitation vs. Mean Monthly Normalised Reflectance Factor Understorey-1	Monthly Precipitation vs. Mean Monthly Normalised Reflectance Factor Understorey-2
Lag	Spearman's rho	Spearman's rho	Spearman's Rho
1	0.909**	0.55	0.5
0	0.884**	0.141	-0.152
-1	0.488	0.092	-0.323
-2	0.012	0.177	0.012

Table 5.48 Correlations between ARS measurements and monthly precipitation

\*Indicates 95% Significance \*\*Indicates 99% Significance

Table 5.49	Correlations	between ARS	measurements and	mean monthl	y relative humidity

	Monthly Mean Relative Humidity vs. Mean Monthly Normalised Reflectance Factor Ground	Monthly Mean Relative Humidity vs. Mean Monthly Normalised Reflectance Factor Understorey-1	Monthly Mean Relative Humidity vs. Mean Monthly Normalised Reflectance Factor Understorey-2
Lag	Spearman's rho	Spearman's rho	Spearman's Rho
1	0.292	0.293	0.478
0	0.674*	-0.019	0.233
-1	0.68*	-0.019	-0.022
-2	0.626	0.138	0.025

\*Indicates 95% Significance \*\*Indicates 99% Significance

Table 5.50 Correlations between ARS measurements and mean monthly evaporation

	Monthly Mean Evaporation vs. Mean Monthly Normalised Reflectance Factor Ground	Monthly Mean Evaporation vs. Mean Monthly Normalised Reflectance Factor Understorey-1	Monthly Mean Evaporation vs. Mean Monthly Normalised Reflectance Factor Understorey-2		
Lag	Spearman's Rho	Spearman's Rho	Spearman's Rho		
1	0.623	0.706*	0.543		
0	0.466	0.411	0.388		
-1	0.214	-0.583	-0.489		
-2	0.098	0.568	0.321		

\*Indicates 95% Significance \*\*Indicates 99% Significance

## **Conclusions:**

- 1. The automated acquisition of standardised reflectance measurements is an effective method of monitoring changes in vegetation amount and condition, providing canopy  $\tau$  is nil or constant. Differences in illumination conditions can factored out using remotely sensed imagery.
- 2. Results from the Las Trancas verification site have indicated that the positioning of the photo-diodes above the vegetation is crucial in providing good, unambiguous estimates of integrated vegetation reflectance changes over time.
- 3. Caution must be exercised when interpreting data acquired within the canopy, since near infrared enrichment of incident EMR may occur when the canopy increases in areal extent and/or volume. This may act to amplify monitored NIR reflectance measurements in the understorey and attenuate visible reflectance.

#### 5.3 SUMMARY

Although the measurements and observations discussed in this chapter are probably best described as indicative rather than definitive they do allow a quantification of the biological phenological changes that have occurred at each of the ground verification sites.

At Lomerio, a phenology consistent with a vegetation community that is highly adapted to a seasonal water deficit was observed. For example, during the driest months evapotranspiration losses were minimised by reductions in leaf-area. Across the forest concession, microclimatic variations dictated modifications to the general pattern. This resulted in varying degrees of sensitivity to the general meteorological variations monitored at Las Trancas 14 km distant (see Table 5.51). For example, visual assessments of phenological stage noted a more evergreen response associated with humid microenvironments. In contrast, the ARS system detected a more seasonal ground vegetation phenology associated with a drier open clearing (again see Table 5.51).

A savanna climate was recorded at Las Trancas. The wooded savanna vegetation is highly seasonal, particularly the ground layer which is dominated by annuals whose biomass accumulation is synchronised with water availability. Savanna trees are less seasonal having evolved a plethora of drought management strategies. Although not all tree species are xerophytic, many possess deep roots to exploit groundwater in the dry season. The monitored biological phenology was well correlated with the meteorological observations (Table 5.51). In general vegetation responded quickly to changes in abiotic resources.

At Chapare, a less seasonally variant and significantly wetter climate was recorded. Very few significant correlations were revealed between biological phenology and meteorological parameters (Table 5.51).

Table 5.51 Summary of the correlations between phenological measurements and the meteorological data

		Seasonal semi-deciduous TF			Si	Savanna Aborizada				Seasonally-inundated TF			
Mo: -1 0 +1	st Significant Lag (previous month) (contemporaneous) (subsequent month)	Mean monthly temperature	Monthly precipitation	Mean monthly relative humidity	Mean monthly potential evaporation	Mean monthly temperature	Monthly precipitation	Mean monthly relative humidity	Mean monthly potential evaporation	Mean monthly temperature	Monthly precipitation	Mean monthly relative humidity	Mean monthly potential evaporation
	Litterfall Measurements	-1	+1	+1	+1	No Data	No Data	No Data	No Data	No significant correlation	No significant correlation	No significant correlation	No significant correlation
	Phenological Observations Leaf Flushing	0 -1	0 -1	0 -1	0 -1	No significant correlation	No significant correlation	No significant correlation	No significant correlation	No significant correlation	No significant correlation	No significant correlation	No significant correlation
	Phenological Observations Photosynthetic ally Active Leaves	0 -1	0 -1	0 -1	0 -1	0	0	0	0	No significant correlation	No significant correlation	No significant correlation	No significant correlation
	Phenological Observations Leaf Senescnce	0 -1	0 -1	0 -1	0 -1	0	0	0	0	No significant correlation	No significant correlation	No significant correlation	No significant correlation
	Canopy Openness	0 -1	0 -1	-1	No significant correlation	+1	+1	0	0	No significant correlation	-1	No significant correlation	No significant correlation
	Derived LAI	1	0	0	0	No Data	No Data	No Data	No Data	0	No significant correlation	No significant correlation	No significant correlation
	Ground reflectance	No significant correlation	0	0	0	-1	0	0	0	No significant correlation	+1	No significant correlation	No significant correlation
	Understorey reflectance	No significant correlation	No significant correlation	No significant correlation	No significant correlation	-1	0	0	0	No significant correlation	No significant correlation	No significant correlation	+1

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# CHAPTER 6 ANALYSIS OF THE SPECTRAL PHENOLOGY OF SATELLITE SENSOR DATA (1.1 km DATASET)

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# CHAPTER 6 ANALYSIS OF THE SPECTRAL PHENOLOGY OF SATELLITE SENSOR DATA (1.1 km DATASET)

## 6.1 INTRODUCTION

In Chapter 4 the processing chain for remotely sensed data collected for the three verification sites was discussed. The key information regarding data processing is given in Table 6.1. All the products listed, in this table, are cloud-free, co-registered, corrected for atmospheric perturbations and calibrated for sensor radiometric changes.

	Composite Time-Period		TOHICLIO		Lomerio	-	Lomerio	E	Las I rancas	L.	Las I rancas	T an T	Las I faucas	Chanana	Спараге	Chanara	Спараго	Chanare	Спараго
Degrees +/- Nadir		1	0	2	:0	3	60	1	0	2	0	3	0	1	0	2	0	3	0
	All Images (No. of Images)	\$	3	2	2	3	0		7	2	3	3	1	1	7	1	9	3.	4
Composite Procedure		MVC	Mean-VC	MVC	Mean-VC	MVC	Mean-VC	MVC	Mean-VC	MVC	Mean-VC	MVC	Mean-VC	MVC	Mean-VC	MVC	Mean-VC	MVC	Mean-VC
Degrees +/- Nadir		10	10	20	20	30	30	10	10	20	20	30	30	10	10	20	20	30	30
	5 Days (No. of Images)	8	8	19	19	22	22	7	7	19	19	22	22	16	16	17	17	23	23
	15 Days (No. of Images)	7	7	14	14	16	16	7	7	15	15	16	16	12	12	13	13	15	15
	30 Days (No. of Images)	7	7	11	11	12	12	7	7	12	12	13	13	11	11	11	11	11	11

Table 6.1 Summary of the AVHRR data selection and compositing procedures

This chapter presents the spectral phenologies derived from these data. The comparative analysis of these data with the biological phenological monitoring and meteorological information will be undertaken in Chapter 7.

Spectral phenological data were derived in two stages. Firstly, analysis focused, on monitoring TF reflectance dynamics, within the spectral-temporal domain (section 6.1). Seasonal changes in AVHRR Channels 1 and 2 were analysed by employing three commonly-used vegetation indices (NDVI, SAVI and GEMI). This analysis was undertaken at the single-pixel level (i.e. by observing the pixel where the field verification experiments were located); and at an adjacent area level (i.e. where monitoring was undertaken over a larger area surrounding each field site). Secondly, spatial-temporal changes were analysed by employing local variance measures to detect changes in spatial pattern (section 6.2). Here the absolute changes in reflectance are subordinate to the interpretation of spatial variance changes in the area adjacent to each field verification site.

#### 6.2 ANALYSIS OF SPECTRAL PHENOLOGY

The monitoring of spectral phenology focused initially on detecting reflectance changes, at the ground verification sites, where seasonal changes in vegetation had been measured (Chapter 5). Three different sampling schemes were experimented with:

- (i) monitoring the single pixel attributed to each ground verification area;
- (ii) monitoring a cluster of 5 pixels centred around each ground verification site, these were averaged with a centre-weighted bias, (Figure 6.1);
- (iii) monitoring the mean of a 9-pixel kernel centred on the ground verification area.

A one-way analysis of variance (ANOVA) was calculated on the results from all three sampling schemes. The null hypothesis was that all samples came from the same group. A very low F statistic (supporting the hypothesis) was obtained. Scheme (i) was used to calculate the vegetation indices, presented in the remainder of this chapter, because it was computationally simpler.

Spectral phenological monitoring was then expanded to larger, adjacent areas encompassing a 15 x 15 (225) pixel-kernel centred on each ground verification site. The rationale behind monitoring this larger area was to investigate whether seasonal reflectance changes at this broader spatial scale would provide a similar spectral phenology to those monitored at the single pixel level. At the seasonally-inundated TF verification site, anthropogenic disturbance in the adjacent area meant only an 8 x 8 pixel kernel could be defined (Figure 3.3). In addition, as the area monitored increased in size, the incidence of cloud resulted in, slightly fewer images being available for temporal analysis (Table 6.2).

		Lomeric	)	L	as Tranc	cas	Chapare			
Degrees +/- Nadir	10	20	30	10	20	30	10	20	30	
(No. of Images)	5	12	20	4	11	20	13	13	26	

Table 6.2 Summary of the AVHRR image selection procedures for adjacent area monitoring

#### 6.2.1 Vegetation indices

Three commonly used vegetation indices were employed to monitor spectral phenological change at the three verification sites; NDVI, SAVI and GEMI (cf. section 2.8.2). Only the SAVI and GEMI are discussed in this section since they are less well known than the NDVI.

The soil adjusted vegetation index (SAVI) is based on the NDVI and takes the form:

$$SAVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red} + L} * (1+L)$$
 [6.1]

L is a soil scaling factor (usually 0.5) introduced to account for first-order soil background variations (Huete, 1988). Qi *et al.* (1994) demonstrated that L approached zero at high vegetation covers and that it approached one at low vegetation covers. The optimal value for L will vary therefore with vegetation density and vary seasonally. Since this study uses time-series of vegetation indices the inclusion of a variable L factor was considered but rejected since a loss of vegetation dynamic response will result if L is larger than the red reflectance values. SAVI ( $_{L=0.5}$ ) has been demonstrated to be more effective at detecting vegetation change in a discontinuous grassland than the NDVI (Huete *et al.*, 1992; Huete *et al.*, 1994). Therefore, it was anticipated that the SAVI would be particularly useful, at the Savanna Aborizada verification site, where a strong soil reflectance component was anticipated for at least part of the year.

The Global Environment Monitoring Index (GEMI) devised by Pinty and Verstraete (1992b) was calculated:

$$GEMI = \eta(1 - 0.25\eta) - \left[\frac{\rho_{\text{Red}} - 0.123}{1 - \rho_{\text{Red}}}\right]$$
[6.2]

Where:

$$\eta = \frac{2(\rho_{NIR}^2 - \rho_{Red}^2) + 1.5\rho_{NIR} + 0.5\rho_{Red}}{\rho_{NIR} + \rho_{Red} + 0.5}$$
[6.3]

GEMI was designed specifically for AVHRR multi-temporal studies and acts to attenuate further the affects of varying atmospheric, illumination and soil conditions (Pinty and Verstraete, 1992b).

#### 6.2.2 Analysis of spectral phenology at the verification sites

At a 1.1 km<sup>2</sup> spatial resolution, many seasonally variant reflectance components may be integrated within a remotely sensed signal. Reflectance from vegetation elements (primarily leaves and their supporting structures) will contribute to this integrated reflectance in a complex manner through the interaction of canopy openness, LAI, chlorophyll concentration, LAD and shadowing affects (cf. section 2.5.4). Reflectance from all these components will vary seasonally as a function of phenological stage (cf. section 2.5.5).

#### 6.2.2.1 Seasonal semi-deciduous tropical forest site

At the semi-deciduous forest site, all three vegetation indices produced similar, sinusoidal seasonal patterns (Figures 6.4-6.15). All indices exhibit low values between July and September 1995, and a rapid increase during October and November. A data gap followed in January, after which there was a gradual decline in all indices from March until the end of the monitoring period in August 1996.

The different view geometry classes (i.e. +/- 10, -20 and 30 degrees nadir) did not produced significantly different results (Figures 6.4; 6.8 and 6.12). The contention of some authors (e.g. Hill, 1996) that look angle is more important than phenology in determining reflectance is not valid for moderate view angle changes at this verification site.

The spectral phenological changes monitored at the single pixel level (which are specific to the ground verification site) and the larger adjacent area did not demonstrate significant differences (Figure 6.4). Using these data alone, a highly seasonal vegetation cover would be inferred. However, what is the nature of this cover?

The soils at Lomerio have a high organic matter content. This will result in low visible and NIR reflectance values. Granitic (bare rock) outcrops, which are highly reflective in the visible wavelengths, punctuate the forest landscape resulting in the Lomerio verification site being a mosaic of spectrally different surfaces: vegetation canopy, understorey, organic rich soil and granitic outcrops. During the dry winter season, the canopy is at its most open and LAI is low; the substrate (soil and granite) components will have their maximum influence on integrated reflectance therefore, leading to low VI values. Wood and leaf litter will also be important reflectance components in this season acting to reduce specular reflection at the ground surface. In the wetter summer months, small ephemeral rivers and standing ponds form. These have the effect of reducing near infrared reflectance from the ground. Canopy openness and leaf area is, however, considerably higher during the wet season resulting in the inputs of ground reflectance components into the integrated signal being minimised.

But could such a NDVI temporal profile only be caused by a semi-deciduous tropical forest? Another explanation exists, it is that that this is the result of a seasonal savanna grassland. Batista *et al.* (1997) compared an 'aseasonal' TF with a seasonal forest (*caatinga*) and a savanna (*cerrado*) (Figure 6.40). They comment that a differentiation of seasonal forest from savanna is difficult (on the basis of NDVI time-series alone) and depends primarily on the area attributed to each cover type (and the classification system used).

#### 6.2.2.2 Savanna Aborizada

Seasonal variations in the vegetation indices at the Savanna Aborizada site (Figures 6.16-6.27) were similar to those described for Lomerio. All three VIs produced similar measures of the seasonal vegetation dynamics.

Differences between the single pixel and adjacent area SAVI indices (Figure 6.16) again do not demonstrate significant differences. Changes in view geometry (Figures 6.16; 6.20 and 6.24) are again minimal (within  $\pm$  30-degrees of nadir) and have no discernible impact on any of the vegetation index time-series.

During the dry winter season, soil-dominated reflectance resulted in very low VIs at this site. Rapid increases in the indices occurred after September. It is postulated that this is principally due to the growth of ground vegetation resulting in strong vegetative absorption of EMR in the visible wavelengths and reflectance at the near infrared wavelengths. The influence of the soil reflectance component is attenuated at this time. Consequently, VI values rise during October and November and reach their maximum in December. A substantial data gap occurs in January and February. The vegetation indices remain relatively high until April, after which they decline rapidly. The lowest VIs are found at the beginning of August. This decline is best described in the GEMI.

It is difficult to distinguish the Las Trancas and Lomerio verification sites on the basis of their phenological curves alone. Las Trancas has a greater standard deviation in its recorded reflectance values, but the continuum from savanna woodland (*cerrado*) to seasonally semideciduous tropical forest is an ecotone. In this context, limiting the local environment monitoring area to 15km<sup>2</sup> was a prudent measure.

#### 6.2.2.3 Seasonally-inundated tropical forest

All three VIs for the seasonally-inundated TF verification site produced similar temporal patterns (Figures 6.28-39). The indices were moderate to high at the start of the monitoring period in June and July. By late August, and through September, there was a marked rapid decline in the vegetation index values. This was followed by an increase in the VIs until they recovered values similar to those in June and July by December. The indices were then relatively stable until March when a further decline and subsequent increase occurred. By June 1996 VIs had again risen to their initial levels. All three VIs display the same seasonal trends, however GEMI is distorted by an exceptionally high value in December.

There are clear differences between the indices derived for the single pixels and adjacent areas at this verification site (Figure 6.28). The temporal selection process (adjacent area, Table 6.2) removed the imagery which led to the second trough in VIs in March. Using the adjacent area monitoring scheme alone, a semi-evergreen TF with a moderate dry season litterfall might be hypothesised. Single pixel monitoring would reveal a forest with a double leaf fall phenology.

Changes in view geometry (Figures 6.28; 6.32 and 6.36) are minimal (within +/- 30degrees of nadir) and have no discernible impact on any of the vegetation index time-series.

#### 6.2.3 Summary of the spectral phenologies

Similar spectral phenologies emerged for the three verification sites. The salient points concerning these phenologies are as follows.

- The semi-deciduous TF and Savanna Aborizada verification sites exhibit a single seasonal trough in VIs associated with vegetation senescence, in the dry season, and a single peak of VIs in the wet season.
- Single pixel monitoring proved representative of spectral phenological changes of the wider c.15km<sup>2</sup> area around the semi-deciduous TF and Savanna Aborizada verification sites.
- 3. The seasonally-inundated TF verification site, when monitored using the single pixel technique exhibited two periods of reduced VI values. When the spectral changes in the adjacent area were monitored only one period of reduced VIs was noted.
- 4. The contention that differences in AVHRR view geometry may have a greater determining affect on spectral reflectance than tropical vegetation phenological change (Hill, 1996) can not be substantiated in these analyses of spectral phenology. No significant differences were noted between the forward and backward view angles at Lomerio (Figures 6.4, 6.8 and 6.12); Las Trancas (Figures 6.16, 6.20 and 6.24) or Chapare (Figures 6.28, 6.32 and 6.36).
- 5. NDVI and SAVI provided similar spectral phenologies for all sites. This is unsurprising since they are based on the same normalised difference reflection function. Results from all the sites are compared on Figure 6.2 in which a linear association is apparent. The GEMI produced comparable spectral phenologies to the NDVI (Figure 6.3). However, the ranges of the high value were expanded, compared to NDVI and SAVI and the ranges of the low values compressed.

#### 6.3 ANALYSIS OF SPECTRAL-SPATIAL PHENOLOGY

The spatial-temporal monitoring approach is based on the hypothesis that phenological changes may induce changes in the spatial structure of an image, i.e. that the relationships between landscape elements may change seasonally (at different spatial scales). Landscape ecology theory provides a suitable concept to investigate this possibility namely domains of scale (Turner et al., 1989). A domain of scale is defined as a range of spatial scales across which the processes that influence the spatial pattern will be relatively stable, i.e. a range of spatial scales associated with a set of environmental processes. Since the scale of temporal monitoring (i.e. 1km<sup>2</sup>) is constant in this study, the question becomes: what varies seasonally at a spatial scale of 1km<sup>2</sup>? Imagine for example, a scene where the spatial resolution (1km<sup>2</sup>) is considerably finer than the average element size in the scene. Most of the recorded radiance values (in the 1 km pixels) would be highly correlated with their neighbouring pixels. Therefore, a low local variance would be recorded. If the average element size approximates that of the scene resolution elements, the likelihood of pixel values being similar decreases and therefore local variance rises. Woodcock and Strahler (1987) demonstrate that this peak in local variance actually occurs at 0.5 to 0.75 the size of the fundamental scene elements. If the size of the scene elements decrease further, many elements will be found within a single resolution cell and local variance will decline.

The fundamental scene elements at a 1.1 km<sup>2</sup> scale that spatial-temporal monitoring may detect are as follows:

- (i) Differences in the rate and amplitude of phenological change both between, and within, forest communities. These differences may be divided into two groups:
  - (a) those caused by the different microclimatic and hydrological regimes that exist within the TF formations; and
  - (b) those caused by different vegetation responses (i.e. a function of species present).
- (ii) Differences in phenological variations associated with gap size and distribution. Structural variations within TFs will lead to modifications of the microclimate and, most importantly, the light environment conditions. These, in turn, may alter leaf phenology at some spatial scales.
- (iii) Phenological differences in canopy leaf area and density will result in substrate (soil, rock and water) and understorey contributions to integrated reflectance being both seasonally and spatially variant.

#### 6.3.1 Variance analysis

Spatial-temporal monitoring of TF spectral phenology was achieved by means of a moving pixel kernel that applied various measures of variance to the SAVI data of areas adjacent to the monitoring sites (see section 6.1). SAVI was selected for use in the spatial-temporal phenological monitoring since it yielded a large dynamic range of values in the single pixel spectral analysis. When interpreting these textural changes in spectral data it is the relative, rather than absolute, changes in reflectance in the areas adjacent to each verification site which are important. Analyses of temporal changes in spatial variance have certain preconditions:

- (i) no cloud (or cloud shadow) can be present on the image;
- (ii) no artificial disturbance of the vegetation can occur; and
- (iii) the technique cannot be used on spatially composited images (e.g. GAC, GVI) since view geometries could be different for each pixel in the image, i.e. they will vary in a random manner rather than a systematic manner.

Further, since the scene selection criteria was applied to a larger 225 pixel area, patchy cloud and cloud shadows made some images unusable. As a result there were fewer images available for the spatial-temporal analysis than for the other analyses (Table 6.3).

		Lomeria	)	L	as Tranc	as	Chapare			
Degrees +/- Nadir	10	20	30	10	20	30	10	20	30	
(No. of Images)	5	12	20	4	11	20	13	13	26	

Table 6.3 Summary of the AVHRR image selection procedures for spatial monitoring

Measures of mean local image variance (MLIV) were calculated by moving 3 x 3 pixel kernel across each adjacent area image. Total variances were computed, and the means taken as an indication of local variability within the image (Woodcock and Strahler, 1987; Lambin and Strahler, 1994a; 1994b). In each 15 x 15 pixel area tested, all pixels form the centre of the transient kernel once with the exception of the edge pixels which are discounted. Four

measures of variance were calculated: mean Euclidean distance; variance; skewness and kurtosis.

The first-order variance measure mean Euclidean distance was calculated:

Mean Euclidean Distance 
$$= \frac{\sum \left[\sum (x_c - x_{xy})^2\right]^{1/2}}{n-1}$$
 [6.4]

-

Where:

 $x_{xy}$  is the DN value for pixel (x,y), x<sub>c</sub> the DN value of the kernel centre pixel, n the number of pixels in the kernel.

The second order variance measure mean local variance was calculated:

Variance = 
$$\frac{\sum (x_c - M)^2}{n - 1}$$
 [6.5]

Where:

x<sub>c</sub> is the DN-value of the kernel centre pixel,

n is the number of pixels in the window,

M is the mean  $\rho$ -value of the moving window:

$$Mean = \frac{\sum x_{xy}}{n}$$
 [6.6]

The third-order measure of variance, mean local skewness was calculated:

Skewness = 
$$\frac{\sum (x_c - M)^3}{(n-1)(V)^{3/2}}$$

where:

x<sub>c</sub> is the DN-value of the kernel centre pixel,

n the number of pixels in the kernel,

M is the mean of the moving kernel (see above), V is variance (see above).

The fourth-order measure of variance, mean local kurtosis was calculated:

$$Kurtosis = \frac{\sum (x_c - M)^4}{(n-1)(V)^2}$$

[6.7]

Where:

x<sub>c</sub> is the DN-value of the kernel centre pixel,
n the number of pixels in the kernel,
M is the mean of the moving kernel (see above),
V is variance (see above).

Experiments to determine the most appropriate size for the moving kernel of pixels were attempted. However, since the local environment sub-scenes were between 8 by 8 (Chapare) and 15 by 15 (Lomerio and Las Trancas) pixels in dimension, a 3 by 3 pixel kernel represented the only realistic size. The effect of this decision is unknown.

#### 6.3.2 Analysis of spatial phenology at the verification sites

Given that spatial resolution is constant, changes in variance will be a function of either changes in the fundamental scene element size and/or changes in the relative reflectance values attributed to scene elements.

#### 6.3.2.1 Seasonal semi-deciduous tropical forest

Figures 6.41-6.45 demonstrate a pronounced seasonal change in local image variance. In the drier winter period, MLIV is high, whilst in the wetter summer season it is lower. These changes in local variance are inverse to the seasonal pattern of the SAVI (Figures 6.45 and 6.4).

#### **CHAPTER 6, Satellite Observation Results**

Differences in water availability exist within the landscape, these are associated with microtopographic and microclimatological variability. In the dry season, when water is at a premium, these differences are exaggerated. This leads to:

- (i) the canopy being more open, resulting in increased shadowing, multiple scattering and contributions from the ground vegetation and substrate; and
- (ii) differences in phenological stage, attributed to the spatial heterogeneity in the edaphic conditions, being exaggerated.

Many different amplitudes and phases of phenological development are therefore present in the reflectance values of the adjacent areas. Local variance is therefore high. Conversely, in the wet season water balance contrasts in the landscape will be lower. The forest canopy is, at this time, denser, single scattering reflections are more common, and the contribution of the ground and understorey reflectance components (with their differing cell structures and pheno-stages) are reduced. Local variance therefore is low.

#### 6.3.2.2 Savanna Aborizada

The seasonality of change in all the measures of local variance employed at the Savanna Aborizada is great (Figures 6.46 - 6.50). Local variance is high during the dry austral winter months. At this time of the year within the sparsely vegetated savanna landscape, shadows will contribute substantially to recorded reflectance measurements (Pech *et al.*, 1986). Landscape heterogeneity is highest during the rapid greening-up phase in September and October when the contrasts between soil and vegetation are greatest. Community level differences in vegetation structure (i.e. between the drier and wetter savanna formations) will also cause differences in vegetation phenological stage. By January, when the ground layer is fully developed, local variance is much reduced. Again, these changes in local variance are inverse to the seasonal changes in adjacent area SAVI (Figures 6.50 and 6.16). Differences in view geometry may be significant at this site. Views of c.  $\pm 30^{\circ}$  nadir, irrespective of look-direction, tended to produce lower variance estimates. This is probably due to the reduced contribution of the soil component to reflectance at these view geometries.

#### 6.3.2.3 Seasonally-inundated tropical forest

Figures 6.51 - 6.55, all demonstrate high local variance in the drier winter period. Changes in local variance are again inverse to the seasonal changes in adjacent area SAVI (Figures 6.55 and 6.28). Although water is not at a premium in this forest environment, local variance changes are found. One explanation is that differences between the grasslands of the Campo de Buffalo and the mature forests (Figure 3.3) are causing the changes in variance. These will be greatest in the winter (June-October) since the reflectance from the grasslands are then dominated by dry senescent grasses and soil components. Changes in local variance may also result from contrasts between the inundated and terra firme communities within the forested area. The seasonally inundated zones (Figure 3.3) being more evergreen, in the drier winter period, than the terra firme communities. This is since their topography retains water, lessening the impact of the winter dry period in the canopy, and, consequently, reducing leaf abscission. In the wet summer months, water retention in these areas leads to inundation and a more severe wet season leaf fall. Both of these leaf fall modifications would cause increases in MLIV. Unfortunately, the wet-season AVHRR image-dates were not available, in the adjacent area monitoring time-series, to confirm or refute these observations. This was due to the larger 8 x 8 pixel area being cloud contaminated during this period (Table 6.2).

#### 6.3.3 Summary of the spectral-spatial phenologies

- 1. Spatial-temporal analysis detected seasonal variations in mean local variance at all three verification sites.
- 2. These changes have been hypothesised to result from large area phenological differences.
- 3. The greater the contribution of the ground (substrate) and understorey stratum, to the integrated reflectance signal, the greater the mean local image variance. This since reflectance from these strata are a product of diverse microclimatic and edaphic conditions and create a diverse textural contrast against the reflectance from the canopy components. Consequently, their spectral phenological stages (and implied reflectances) will be out-of-phase or of a different amplitude to those of the canopy trees.
- As a result, SAVI and MLIV, are inverse and strongly correlated at all sites (e.g. r=0.71; 95% for Lomerio ±30° nadir).

#### 6.4 SUMMARY

A spectral phenology, for all three verification sites, emerged with a reduction, in VI values, during the drier austral winter period, and an increase, in VI values, during the wetter austral summer. However, the degree of seasonality, in these temporal VI curves, differed greatly between verification sites.

At the seasonally-inundated TF, spectral phenological changes were minimal. Whilst, the semi-deciduous TF and the Savanna Aborizada were characterised by a pronounced seasonal spectral changes. A differentiation of these last two sites was difficult using VIs alone.

Monitoring, the spectral phenology, of a single pixel, generally produced a very similar measure of spectral phenology to that derived from a wider adjacent area (of 225 pixels). Single pixel spectral phenologies are then representative of seasonal changes in the wider vegetation formation. At only one site was this not the case, and this anomaly has been explained by changes in image availability.

Variations in view geometry did not significantly change the shape or magnitude of any of the spectral vegetation indices (in any of the monitored vegetation formations) at the three verification sites.

Spatial-temporal phenological monitoring revealed increases in MLIV in the dry season; and, reductions in MLIV in the wetter austral summer months. These changes were inverse and proportional to the spectral phenological changes documented using VIs. Such a relationship may be explained by the more homogenous nature of the landscape, when canopy vegetation dominates integrated spectral reflectance (and VI values are high). Conversely, in the dry season (lower VIs), a greater diversity of reflectance components contribute to the remotely sensed signal, this leads to a more heterogeneous landscape and resultant increases in local image variance.

# CHAPTER 7 UNDERSTANDING LARGE AREA PHENOLOGY

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## CHAPTER 7 UNDERSTANDING LARGE AREA PHENOLOGY

The aim of this chapter is to compare the ground verification information, presented in Chapter 5, with the satellite-derived data, presented in Chapter 6. Through this synthesis, it is hoped that a better understanding of: (i) the biological significance of spectral phenology; and (ii) the phenological processes that operate at a large area (i.e. >1km) scale within TFs, may be achieved. Implicit in this synthesis will be the concept of spatial integration. Spectral (satellite-derived) phenology represents an integration of many biophysical and abiotic parameters at different spatial scales. At 1 km resolution, this generalisation may result in the detection of a spectral phenology regulting from several different microclimatic regimes, as well as several vegetation communities.

Within this study, two different spectral phenologies have been derived: (i) a purely spectral phenology, obtained by monitoring the changes in reflectance of a single target pixel (section 6.2.1); and (ii) a spatial-spectral phenology. This represents the phenology of the TF landscape by monitoring changes in the spectral reflectance pattern over a c. 15 km<sup>2</sup> adjacent area (section 6.2.2).

Comparison of the ground verification data and the remotely sensed spectral information was achieved in two stages. First, the satellite-derived (spectral) phenological observations were compared to seasonal abiotic changes detected at the two meteorological stations, using measures of statistical association (section 7.1). Next, the relationship between biological phenology (monitored at the three ground verification sites) and the satellite derived (spectral and spectral-spatial) phenological observations were modelled using both multiple regression and factor based analyses (section 7.2).

#### 7.1 ABIOTIC CHANGE AND SPECTRAL PHENOLOGY

The relationship between, satellite derived, spectral phenology and seasonal meteorological changes was investigated as follows. Both the monthly composite SAVI indices, with view geometries of  $\pm/-10$ , 20 and 30° from nadir, (section 6.2), and, the monthly composite local variance index, with a view geometry of  $\pm/-30°$  from nadir, (section 6.3) were tested for association with the following meteorological parameters:

- (i) mean monthly dry bulb temperature;
- (ii) monthly precipitation;
- (iii) mean monthly relative humidity;

- (iv) mean monthly potential evaporation; and
- (v) monthly precipitation minus mean monthly potential evaporation.

This was achieved using the methodology described in section 5.2.1. Correlations were calculated for contemporaneous observations, as well as those lagged by + 1, -1 and -2 months. In order that the timing of rainfall events could be considered, the hypothesis that 'precipitation is more significant to TF phenology when precipitation has been absent or low than when rainfall has been constant or high', was tested by correlating all SAVI observations, with view geometries within  $+/-30^\circ$ , against cumulated daily precipitation. The results of these statistical associations are shown in Tables 7.1, 7.2 and 7.3.

#### 7.1.1 Seasonal semi-deciduous tropical forest

The correlation coefficients between the meteorological variables and SAVI ( $\pm 10$ , 20 and 30° nadir) and MLIV ( $\pm 10$ , 20 and 30° nadir) are shown on Table 7.1

Meteorological	Lag	SAVI	SAVI	SAVI	MLIV
parameters	(in months)	(±10° Nadir)	(±20° Nadir)	(±30° Nadir)	(±30° Nadir)
		Pearson's	Pearson's	Pearson's	Pearson's
		Product moment	Product moment	Product moment	Product moment
Monthly Mean Temperature	1	0.609	0.592	0.661*	0.549
	0	0.77*	0.707*	0.634*	0.703*
	-1	0.535	0.545	0.563	0.562
- <u></u>	-2	-0.395	0.37	0.359	0.9
Monthly Mean Precipitation	1	0.71	0.733*	0.75**	0.77*
	0	0.683	0.601	0.644*	0.782*
<u>, , , , , , , , , , , , , , , , , , , </u>	-1	0.353	0.48	0.489	0.53
	-2	-0.089	0.221	0.357	0.113
Monthly Mean Relative	1	0.7	0.545	0.681*	0.492
Humany	0	0.683	0.853**	0.879**	0.442
	-1	0.764*	0.759**	0.78**	0.383
······································	-2	0.126	0.175	0.195	0.05
Monthly Mean Potential Evaporation	1	-0.66	-0.432	0.598	-0.418
	0	-0.886**	-0.895**	-0.909**	-0.346
	-1	-0.824*	-0.81**	-0.825**	-0.313
<u> </u>	-2	-0.319	-0.281	-0.223	-0.037
(Precipitation - Evaporation)	1	0.738	0.642*	0.73*	0.625
	0	0.892**	0.845**	0.883**	0.551
	-1	0.707	0.751**	0.765**	0.246
	-2	0.192	0.279	0.309	0.07
	*Indic	ates 95% Significanc	e **Indicates 99%	Significance	

Table 7.1 Correlation coefficients (with significance) seasonal semi-deciduous tropical forest

#### CHAPTER 7, Understanding Large-Area Phenology

Figure 7.1 shows the correlation between the meteorological variables and the single pixel SAVI (+/- 10, 20 and 30° from nadir); figure 7.2 shows the meteorological variables and the adjacent area MLIV (+/-  $30^{\circ}$  from nadir). Figure 7.3 plots monthly mean precipitation and SAVI (at +/-  $30^{\circ}$  from nadir); and Figure 7.4 from the daily cumulative precipitation and SAVI (at +/-  $30^{\circ}$  from nadir).

Figures 7.1-7.2 and Table 7.1 reveal a general pattern: the most significant correlations, with meteorological parameters, occur when satellite observations with a  $\pm$  30° from nadir view-geometry are utilised (i.e. five of the correlations are significant at  $\pm$  10° from nadir; nine at  $\pm$  20°; twelve at  $\pm$  30° and three MLIV  $\pm$  30°). This indicates that the increased temporal resolution, offered by a wider viewing geometry, is more important than the absolute precision (in VI values) obtained by limiting view-angles to near identical view-geometries. This refutes Hill's (1996) contention that view angles are more important than phenological changes. Obviously, a trade-off must exist between the two extreme positions. Sufficient temporal frequency must be obtained for time-series analysis, whilst view-angle changes should be minimal. The  $\pm$  30-degrees from nadir sampling scheme represents the best trade-off for this site. No universal rule can be hypothesised however, since factors such as latitude and cloud presence will effect the optimal trade-off between view-angle and image temporal resolution.

The meteorological environment recorded at the Las Trancas AWS (14 km distant from the Lomerio site) is representative of a savanna. Therefore, it is only partially representative of the microclimate in the dry semi-deciduous forests at Lomerio. Within the forest, the humidity levels will be higher; whilst air temperature and precipitation (and consequently potential evaporation) will possibly be lower. These differences will be greatest in the wet season when the canopy will have developed to its full extent. During the dry austral winter, the open canopy of the forest will provide a similar environment to the savanna. The applicability of the Las Trancas meteorological data to this verification site will vary seasonally therefore. Despite these potential differences, significant associations were obtained between the spectral phenology (SAVI and MLIV) and contemporaneous mean monthly temperature and mean monthly precipitation lagged by one month. The immediate question posed by this result is; why high significant correlations were obtained with the subsequent month's rainfall? A negative lag (i.e. a significant correlation with the preceding months rainfall) could be explained on the basis that vegetation may take time to respond to an abundance or absence of precipitation (i.e. change in water availability). This has been recorded in many studies (e.g. Malaisse, 1974; Hubble and Foster, 1986). A positive lag,

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however, indicates some degree of *anticipatory* phenology. This pre-emptive change in leaf area has been reported for other semi-deciduous TFs (Alvim and Alvim, 1978; Borchert, 1980; Reich and Borchert, 1982; Borchert, 1994a). These authors ascribe such changes to a plant's sensitivity to changes in relative humidity levels. Certainly, the mechanism for leaf flushing or abscission must rely on an abiotic cue other than precipitation. When cumulative precipitation and SAVI  $\pm$  30° nadir were correlateded (figure 7.4) an insignificant association of 0.43 was obtained. The hypothesis that 'precipitation is more significant to TF phenology when precipitation has been absent or low than when rainfall has been constant or high' cannot therefore be substantiated.

Mean monthly relative humidity; potential evaporation and precipitation minus evaporation all show significant correlations with both the contemporaneous, and the previous month's SAVI. These strong significant associations are more easily explicable, since a causal relationship can be hypothesised between vegetation phenology and these abiotic stimuli. It seems likely then that at a system level (i.e. that integrated over a 1 km<sup>2</sup> area) the TF vegetation at Lomerio is sensitive to changes in atmospheric humidity and / or water availability. Its leafing strategy may have evolved to anticipate that a sharp rise in humidity (a fall in evapotranspiration rates) is usually followed by significant precipitation event, and *vice versa*. Precious plant water and energy reserves can then be deployed, to leaf production when wet months are expected, or conserved, through leaf senescence and abscission, when a water deficit is anticipated (Borchert, 1980; Reich and Borchert).
## 7.1.2 Las Trancas (Savanna Aborizada)

The correlation coefficients between the meteorological variables and SAVI (±10, 20 and 30°

nadir) and MLIV ( $\pm 10$ , 20 and 30° nadir) are shown on table 7.2

Meteorologica	l Lag	SAVI	SAVI	SAVI	MLIV
parameters	(in months)	(±10° Nadir)	(±20° Nadir)	(±30° Nadir)	(±30° Nadir)
		Pearson's	Pearson's	Pearson's	Pearson's
		Product moment	Product moment	Product moment	Product moment
Monthly Mean Temperature	n 1	0.285	0.322	0.448	-0.061
	0	0.539	0.609	0.566	-0.666
	-1	0.534	0.66*	0.76**	-0.538
	-2	0.661*	0.62	0.654*	-0.712*
Monthly Mean Precipitation	n 1	0.313	0.41	0.489	-0.504
	0	0.622	0.709*	0.735**	-0.613
	-1	0.723*	0.758*	0.785**	-0.822*
	-2	0.321	0.44	0.508	-0.697
Monthly Mean Relative Humidity	n 1	0.243	0.333	0.524	-0.345
	0	0.929**	0.92**	0.921**	-0.634
	-1	0.821*	0.863**	0.808**	-0.822*
	-2	0.239	0.366	0.381	-0.408
Monthly Mean Potential Evaporation	n 1	-0.252	-0.3	-0.481	0.352
	0	-0.936**	-0.906**	-0.905**	0.524
	-1	-0.823*	-0.839**	-0.746**	0.778*
	-2	-0.194	-0.338	-0.3	0.333
(Precipitation Evaporation)	- 1	0.314	0.393	0.534	-0.454
	0	0.899**	0.91**	0.923**	-0.598
	-1	0.859**	0.873**	0.831**	-0.869**
	-2	-0.537	0.258	0.414	0.428
	*India	cates 95% Significan	ce **Indicates 99%	5 Significance	

Table 7.2 Corelation coefficients (with significance) Savanna Aborizada

Figure 7.5 shows the correlations between the meteorological variables and the single pixel SAVI (+/- 10, 20, and 30° from nadir). Figure 7.6 shows the meteorological variables and the adjacent area MLIV (+/-  $30^{\circ}$  from nadir). Figure 7.7 plots monthly mean precipitation vs. SAVI (+/-  $30^{\circ}$  nadir). Finally, Figure 7.8 shows the daily cumulative precipitation vs. SAVI (+/-  $30^{\circ}$  from nadir).

Figures 7.5 - 7.8 and Table 7.2 reveal (eight of the correlations are significant at  $+/-10^{\circ}$  from nadir; nine at  $+/-20^{\circ}$ ; ten at  $+/-30^{\circ}$  and five MLIV  $+/-30^{\circ}$ ) a general pattern that more significant correlations, with meteorological parameters, occur as the satellite view-geometry is widened.

The meteorological environment recorded by the nearby AWS is representative of the local savanna microclimate at Las Trancas. Consequently, many significant correlations were obtained between spectral phenology and meteorological parameters, specifically:

- (i) SAVI and the previous month's mean temperature; and
- (ii) SAVI (and MLIV) and the contemporaneous and previous months monthly precipitation; mean monthly relative humidity; potential evaporation and water balance.

Clearly, the associations between SAVI and these meteorological variables imply no degree of anticipatory phenology. The negative lags may be explained by vegetation taking time to respond (i.e. grow or senescence) to hydro-meteorological changes. However, the fact that correlation coefficients exist for most parameters for the contemporaneous month as well as the previous month suggests a wide time frame of phenological responses. Such vegetation changes may be: (a) extremely rapid in some strata, e.g. the fire phase senescence and subsequent early wet-season greening of the grass dominated ground stratum; or (b) relatively slow in other strata, e.g. the semi-evergreen tree stratum (Killeen and Hinz, 1992a; 1992b). These differences in vegetative response to climatic variations are primarily a function of the dominant life form in the strata. For example, the monocotyledon grasses and sedges that dominate the ground stratum must transform their entire structure since the absence of the petiole prohibits rapid leaf deployment or senescence. Such vegetation has adapted to seasonal water deficits therefore by timing its life cycle so that active growing phase is synchronised with environmental resource availability (Killeen and Hinz, 1992a; 1992b). In contrast, the dicotyledonous trees respond less dramatically to changes in resources by changing only their leaf area (Prasad and Hedge, 1986). In a spectral phenology, the reflectance from these two very different botanical responses to seasonal water deficit are integrated, both spatially and temporally.

The regression of cumulative precipitation and SAVI (+/- 30° from nadir (Figure 7.8) again failed to produce a significant correlation (0.64). The hypothesis that 'precipitation is more significant to TF phenology when precipitation has been absent or low than when rainfall has been constant or high' again cannot be substantiated. Spectral phenology at the savanna site is best described as responsive too, rather than anticipatory of, changes in the availability of environmental water.

## 7.1.3 Seasonally-inundated tropical forest

The correlation coefficients between the meteorological variables and SAVI (±10, 20 and 30°

nadir) and MLIV (±10, 20 and 30° nadir) are shown on 7.3

Meteorologica	l Lag	SAVI	SAVI	SAVI	MLIV
parameters	(in months)	(±10° Nadir)	(±20° Nadir)	(±30° Nadir)	(±30° Nadir)
		Spearman's Rho	Spearman's Rho	Spearman's Rho	Spearman's Rho
Monthly Mean Temperature	n 1	0.545	0.436	0.336	-0.082
	0	0.38	0.264	0.41	-0.705
	-1	0.419	-0.024	0.087	-0.54
	-2	0.358	-0.425	-0.401	-0.624
Monthly Mean Precipitation	n 1	0.463	0.258	0.289	-0.534
	0	0.455	0.178	0.307	-0.622
	-1	0.3676	-0.178	-0.067	-0.795*
	-2	0.228	-0.443	-0.457	-0.625
Monthly Mean Relative Humidity	n 1	0.565	-0.045	0.114	-0.438
	0	0.841**	0.125	0.067	-0.571
	-1	0.395	0.202	0.206	-0.732*
	-2	0.01	-0.234	-0.136	-0.323
Monthly Mean Potential Evaporation	n 1	-0.537	0.073	-0.148	0.464
	0	-0.942**	-0.254	-0.177	0.457
	-1	-0.447	-0.357	-0.299	-0.663
	-2	0.128	0.136	0.08	0.249
(Precipitation Evaporation)	1	0.555	0.074	0.229	-0.538
	0	0.818**	0.245	0.255	-0.548
	-1	0.456	0.176	0.177	-0.772*
	-2	0.025	-0.294	-0.265	-0.45
	*Indic	ates 95% Significant	ce **Indicates 99%	Significance	

Table 7.3 Correlation coefficients (with significance) Seasonally Inundated TF

Figure 7.9 shows the correlations between the meteorological variables and the single pixel SAVI (+/- $10/20/30^{\circ}$  nadir); figure 7.10 the meteorological variables and the adjacent area MLIV (+/- $30^{\circ}$  nadir). Figure 7.11 plots monthly mean precipitation vs. SAVI (+/- $30^{\circ}$  nadir); and figure 7.12 the daily cumulative precipitation vs. SAVI (+/- $30^{\circ}$  nadir).

Figures 7.9 - 7.12 and Table 7.1.3 reveal few general trends for any of the meteorological variables. Only six of the 80 correlation coefficients are significant at 95%, compared to 29 of 80 at Lomerio and 32 of 80 for Las Trancas. This suggests that the meteorological parameters have less direct influence a spectral phenology in the seasonally inundated forest than in the drier deciduous forest and savanna. Since there is always an abundance of water in the

environment, leaf phenology probably tends towards a variety exchange mechanisms to renew leaves, which result in no pronounced leaf-less periods and a low degree of deciduous synchronisation (Gordon *et al*, 1974; Hopkins and Graham, 1989; Putz, 1979; Medway, 1972). The mix of leaf flush and abscission phenologies (observed in section 5.2) results in an integrated semi-evergreen spectral phenology. The general lack of correlation between the meteorological parameters and the spectral phenological indices probably results therefore from the limited seasonal variability that occurs within both datasets. This has been reported for other aseasonal neotropical forest formations (e.g. Batista *et al.*, 1997; Justice *et al.*, 1987).

The correlation of cumulative daily precipitation and SAVI +/-  $30^{\circ}$  from nadir produced an insignificant correlation of 0.01 (figure 7.12). The hypothesis that 'precipitation is more significant to TF phenology when precipitation has been absent or low than when rainfall has been constant or high' is rejected.

# 7.2 COMPARISON OF BIOLOGICAL AND SPECTRAL PHENOLOGIES

The relationship between spectral phenology and seasonal vegetation change, monitored on the ground (biological phenology), is best described by parameters that account for the modification of EMR by vegetation. Since the principal plant organ for intercepting EMR is the leaf, biophysical variables that include some quantification of leaf presence, area or quantity will be most useful, i.e. LAI, biomass or crown cover. The relationship between these variables and spectral vegetation indices is well documented e.g. Jordan (1969); Lillesand and Kiefler, (1987); Asrar *et al.*, (1989) Justice *et al.* (1989); Achard and Blasco (1990); Derrien *et al.* 1992; Pinty and Verstraete (1992); Millington *et al.* (1994); Myneni and Williams (1994); Myneni *et al.* (1997). These relationships were reviewed in section 2.8.

At a large area (i.e. >1 km<sup>2</sup>) scale differences in vegetation community composition; leaf structure (chlorophyll content); microclimate; micro-topography; substrate and soil moisture, as well changes in leaf area may be important. The combination of some of these factors will result in a diversity of canopy patterns and understorey vegetation densities. The heterogeneity of tropical forests, at most spatial scales, will cause a large within-site variance in the biological phenology that is observed (Townshend *et al.*, 1987). This variance, as well as the botanical seasonality, will be present in both the integrated spectral signal and the monitored ground verification parameters (i.e. in this study; total litterfall; leaffall; derived LAI; canopy openness; red and near infrared reflectances in the vegetation).

McDonald *et al.* (1997) report that for a simulated forest scene, SAVI is a function of: ground reflectance LAI, crown cover, solar zenith angle in the following proportions 0.6%; 0.1%; 94.8% and 2.1% respectively. Their study serves illustrate that LAI alone may be a relatively unimportant biophysical parameter in integrated spectral response. When combined with factors such as LAD, foliage clumping and shadow components (which are implicit within a composite variable such as crown cover, or canopy openness) a far greater degree of realism is attained and the parameter gains a greater relative importance (significance).

For the purposes of comparing the spectral and biological phenologies, the ground monitored techniques were divided into three groups.

- (i) Direct measurements, i.e. the litterfall measurements and visual assessments of phenological condition. In this group, no spatial integration of measurements has occurred. Results are a function of a single, simple biological parameter changing, e.g. a leaf-falling or a bud bursting.
- (ii) Semi-integrated techniques, i.e. hemispherical photography and ceptometry. In this category some degree of integration of phenomena has occurred. Although the primary 196 -

determining parameter is leaf-area, changes in leaf angle distribution or mutual shadowing result in an integration of more than one biophysical characteristic.

(iii) Integrated techniques, i.e. automated radiometry measurements. In this group, many biotic and abiotic variables have been spatially integrated. Measurements account for vegetation LAI, LAD, biomass and chlorophyll concentration / efficiency; as well as changes in soil water and soil organic matter and shadowing reducing them all into a single integrated index.

Given that the remotely sensed spectral signal is an integration of all the factors listed in (iii), associations between spectral phenology and this group are likely to be higher than the semiintegrated and direct measurements. As the degree of integration decreases significant associations probably decline.

## 7.2.1 Regression modelling

In this section, the relationship between biological and spectral phenology is modelled using multiple regression analysis. This procedure is well suited to quantifying time-lagged and integrated data (Huete *et al.*, 1994). Since modelled associations may be linear, concave, convex, exponential or logarithmic the data were screened graphically using scatter plots (Figures 7.13 - 7.25) to determine the most appropriate type of model. Experimentation revealed that a linear model yielded the most consistent results, i.e. where the residuals were randomly distributed and normal. The model was run in a step-wise mode, i.e. the independent variable having the highest correlation, with the dependent variable, being entered first.

At the seasonal semi-deciduous site (Lomerio) the following ground verification data: (i) total litterfall; (ii) leaffall; (iii) derived LAI; (iv) canopy openness; and (v) the ARS-NDVI monthly maximum value ground reflectance, were initially regressed, individually, against the contemporaneously-derived SAVI (+/- 10, 20 and 30° from nadir) and MLIV (+/-  $30^{\circ}$  from nadir). Subsequently all five variables were regressed against contemporaneously-derived SAVI (+/- 10, 20 and  $30^{\circ}$  from nadir).

At the Savanna Aborizada site (Las Trancas) the following ground verification data: (i) canopy openness; (ii) ARS-NDVI monthly maximum value ground-1 reflectance; (iii) ARS-NDVI MVC ground-2 reflectance; and (iv) ARS-NDVI MVC tree reflectance; were first regressed individually against the contemporaneously derived SAVI (+/- 10, 20 and 30° from

nadir) and MLIV (+/-  $30^{\circ}$  from nadir). Then all four variables were regressed against contemporaneously-derived SAVI (+/- 10, 20 and 30° from nadir) and MLIV (+/-  $30^{\circ}$  from nadir).

At the seasonally inundated TF site, the following ground verification data were used. Total litterfall, leaffall, derived LAI, canopy openness and the ARS-NDVI monthly maximum value ground reflectance. These were correlated individually (using Spearman's rho) against the contemporaneously derived SAVI (+/- 10, 20 and 30° from nadir) and MLIV (+/- 30° from nadir). No regressions could be carried out on these data because of their non-parametric nature.

## 7.2.2 Biological phenology vs. spectral phenology

In this section, the associations between the single pixel spectral phenology (SAVI) and the ground verification variables (biological phenology) are analysed.

## 7.2.2.1 Lomerio (Seasonal Semi-Deciduous Tropical Forest) Site

At Lomerio five measures of biological phenology were regressed against the monthly composite SAVI (+/-  $10/20/30^{\circ}$  nadir). The results are shown in Tables 7.4 and 7.6 and equation 7.1.

Table 7.4 Regre	ssion and Cor	rrelations obt	ained between	n SAVI and ground observations:
	Lomerio (	seasonal sem	i-deciduous tr	ropical forest)
Lomerio	Lag 0 (	(Contempor	aneous)	▲Indicates 90% Significance
	SAVI	SAVI	SAVI	*Indicates 95% Significance

Lomerio	Lag U	(Contempora	ineous)
	SAVI (±10° Nadir)	SAVI (±20° Nadir)	SAVI (±30° Nadir)
	Multiple (r)	Multiple (r)	Multiple (r)
Total Litter & Derived LAI & Canopy Openness & ARS Ground	0.951	0.925	0.95*
	Regression	Regression	Regression
	Coefficient (r)	Coefficient (r)	Coefficient (r)
Total Litterfall	0.375	0.253	0.513
Leaffall	0.276	0.132	0.478
Derived LAI	0.758*	0.758*	0.777**
Canopy Openness	0.599	0.599₩	0.632*
ARS Ground reflectance	0.862**	0.862**	0.895**

SAVI<sub>30</sub> = {2.138(ARS Ground)} + {-5.491(LAI)} + {-5.42(Canopy Openness)} + {-4.62(Litterfall)} + 0.543

\*Indicates 99% Significance

Only the SAVI +/- 30° from nadir observations provided a stepwise multiple regression with significant results (equation 7.1). However, this reveals nothing of the relative importance of the independent variables, because the values of the partial regression coefficients reflect the original units in which the variables were measured. The Beta units have therefore been included (Table 7.2). These describe the number of standard deviations of change on the dependant variable that will be produced by a change of one standard deviation in the independent variable concerned.

Table 7.5 Beta units for equation 7.1

	ARS Ground reflectance	Derived LAI	Canopy Openness	Total Litterfall
Beta	1.086	0.42	-0.179	-0.18

Now it is clear that the strongest association exists between SAVI (+/- 30 degrees from nadir) and the ARS ground reflectance data. A change in ground based reflectance resulting in SAVI changes of almost the same magnitude. Derived LAI also has a strong relationship with the SAVI. The other two biological phenological variables (canopy openness and litterfall) have less strong negative associations.

The ground ARS measurements, LAI and canopy openness all produced significant correlations independently. The most significant correlations occurring with SAVI view geometries (+/-  $30^{\circ}$  from nadir). The ground ARS measurements produced significant associations with all SAVI view geometries.

The order of significance of these verification procedures reflected the type of ground monitoring technique used. For example, the integrated technique (i.e. the automated radiometry measurements) produced the most significant results, followed by the semi-integrated techniques (hemispherical photography and ceptometry). The direct measurement technique (litterfall monitoring) failed to produce any significant correlations with spectral phenology (Table 7.4). This was the expected trend (cf. section 7.2); the degree of integration of the ground monitoring parameter predetermining its relationship to remotely-sensed spectral integrations.

Canopy openness and derived-canopy LAI both showed similar and significant independent correlations with spectral phenology. This establishes that ground monitored canopy dynamics are synchronised with the spectral phenological changes observed using remote sensing. The canopy contribution to the integrated reflectance signal is significant; but it does not explain all of the variation in spectral phenology due to the following factors. First,

at high LAI values an asymptote of reflective response will be reached, especially in the visible wavelengths (Goel, 1988). Secondly, the integration effects arising from LAD, seasonal changes in sunlit leaf-fraction / shadowing, and the off-nadir view geometry are likely to contain non-linear attributes not accounted for in the regression model. Thirdly, the ground reflectance contribution is unaccounted for. Indeed, the ARS ground measurement correlation is very high (and significant) suggesting that the ground stratum may play an important role in integrated reflectance for a large part of the year and in particular, when most of the canopy leaves have been shed. The effect of specialised ground vegetation such as the  $C_3$  (Calvin pathway) grasses, which are adapted to capture of PAR in the low-light intensity environment of tropical forests, may act to reduce the impact of dry season canopy leaf area reductions (Killeen and Hinz, 1992a; Allen *et al.*, 1974).

## 7.2.2.2 Savanna Aborizada

At Las Trancas, four measures of biological phenology were regressed against the monthly composite SAVI (+/- 10/20/30-degrees nadir). The results are shown on Table 7.6; 7.7 and equations 7.2 and 7.3.

Las Trancas	Lag 0 (C	Contemporan	eous)
	SAVI (±10° Nadir)	SAVI (±20° Nadir)	SAVI (±30° Nadir)
	Multiple (r)	Multiple (r)	Multiple (r)
Canopy Openness & ARS Ground-1 & ARS Ground-2 & ARS Tree	0.915	0.901*	0.923*
	Regression	Regression	Regression
	Coefficient (r)	Coefficient (r)	Coefficient (r)
<b>Canopy Openness</b>	0.736₩	0.778**	0.831**
ARS Ground-1	0.859*	0.883**	0.915**
ARS Ground-2	0.906**	0.877**	0.898**
ARS Tree	0.845*	0.844**	0.78**

Table 7.5 Regression and Correlations obtained between SAVI and ground observations: Las Trancas (Savanna Aborizada)

SAVI<sub>30</sub> = {1.392(Ground-1)} + {0.647(Ground-2)} + {-0.709(Canopy Openness)} + {-1.29(Tree)} + 7.6

[7.2]

✤Indicates 90% Significance \*Indicates 95% Significance \*\*Indicates 99% Significance

 $SAVI_{20} = \{1.636(Ground-1)\} + \{0.811(Ground-2)\} + \{-2.765(Canopy Openness)\} + \{-1.13(Tree)\} + 7.35(Canopy Openness)\} + (-1.13(Tree))\} + 7.35(Canopy Openness)\} + (-1.13(Tree)) + 7.35(Canopy Openness)] + 7.35(Canopy Open$ 

[7.3]

Again, to determine the relative importance of the independent variables the Beta units have been included.

	Ground-1	Ground-2	Canopy Openness	Tree
Beta (SAVI <sub>30</sub> )	0.857	0.693	-0.467	-0.154
Beta (SAVI <sub>20</sub> )	1.136	0.555	0.037	-0.839

Table 7.7 Beta units for equations 7.2 and 7.3

At this site, the strongest associations exist between SAVI (+/- 20 and 30 degrees from nadir) and the ARS ground reflectance data. The other two biological phenological variables (canopy openness and tree reflectance) have less strong negative associations.

All SAVI view angle geometries produced significant correlations with the ground verification measurements. Indeed, almost all spectral phenological changes, at this site, can be explained by the monitored ground parameters. It seems probable then that the biophysical parameters and phenological changes were more accurately defined and monitored by the ground techniques employed at this site. Given that the same techniques were used at all three sites it is likely that the nature of phenological variations in this landscape are simpler and easier to characterise. Certainly, the ARS ground monitoring diodes appear to closely mimic the reflectance received at the satellite. The ARS diode pair (above the tree), which occupied the highest position, and therefore integrated the greatest diversity of TF landscape reflectance components, also produced highly significant correlations. These were not the highest correlations however and it may be that the tree landscape elements (with attendant shadow cast by the tree crown and leaf size structure), are over represented in this diode pair reflectance-integration.

# 7.2.2.3 Chapare (Seasonally Inundated Tropical Forest)

At Chapare five measures of biological phenology were correlated against the monthly composite SAVI (+/- 10, 20 and 30° from nadir). No regression based modelling was possible because of the nonparanetric nature of the data. The results are shown on Table 7.8.

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★Indicates 90% Significance \*Indicates 95% Significance \*\*Indicates 99% Significance

Chapare	Lag 0 (Contemporaneous)				
salera vere -	SAVI (±10° Nadir)	SAVI (±20° Nadir)	SAVI (±30° Nadir)		
	Spearman's rho	Spearman's rho	Spearman's Rho		
<b>Total Litter</b>	0.317	0.285	0.115		
Leaf Litter	0.276	0.234	0.134		
Derived LAI	0.486	0.501	0.438		
<b>Canopy Openness</b>	0.08	0.072	0.148		
ARS Ground	0.122	0.143	0.713*		

 Table 7.8 Spearmans' Rank correlations obtained between SAVI and the ground observations:

 Chapare (seasonally-inundated tropical forest)

Only one significant result was obtained from these correlations; that between the ARS ground measurements SAVI  $\pm 30^{\circ}$  from nadir. Given the aseasonal nature of both the biological and spectral phenological databases at this site, this result may be a type-1 error.

Correlations between derived LAI and SAVI yield, however, consistently high (but nonsignificant) correlations, indicating that perhaps LAI is an important component in the spectral phenology of this site. This might suggest that there is perhaps some biological basis for spectral phenology (in a seasonally-inundated TF) but not at the 90% significance level. Canopy openness (derived from hemispherical photography) displays very low correlations at this site. Again, this need not necessarily imply a lack of seasonal variation. The differing structure of a seasonally-inundated successional forest may bias canopy openness estimations since the a dense understorey may obscure the camera view of canopy dynamics. Similarly, litterfall represents an integration of the whole forest section above the trap. Since no specific strata is targeted it may be that this is to general parameter to study phenology at this site.

# 7.2.3 Biological phenology vs. spectral-spatial phenology

In this section, the associations between mean local image variance (i.e. the spatial interactions of the c. 225 pixels that make up each adjacent area, cf. section 6.2) and the ground-monitored (biological) phenology are examined.

## 7.2.3.1 Lomerio (Seasonal Semi-Deciduous Tropical Forest) Site

At Lomerio, the five measures of biological phenology were regressed against the monthly composite MLIV (+/-30-degrees nadir). The results are shown on Table 7.9.

	<u>entemperan</u>	(ous)
	MLIV (±30° Nadir)	▼Indicates 90% Significance
	Multiple (r)	*Indicates 95% Significance
Total Litter & Derived LAI & Canopy Openness & ARS Ground	0.862	
	Regression	
	Coefficient (r)	
Total Litter	0.641₩	
Leaf Litter	0.453	
Derived LAI	0.779*	
<b>Canopy Openness</b>	0.838**	
ARS Ground	0.497*	

Table 7.9 Regression and correlations obtained betweenMLIV and ground observations: Seasonal Semi-Deciduous Tropical ForestLomerioLag 0 (Contemporaneous)

Changes in the spatial structure of the adjacent area image are significantly correlated with four of the five measures of biological phenology. Canopy openness produced the most significant result followed by the other integrated ground parameters. However, the linear combination of the five biological phenological parameters failed to produce a significant result.

The scene elements that will contribute most to spatial changes at this spatial scale are likely to be c. 2-3 km<sup>2</sup> in size according to Woodcock and Strahler (1987). Vegetation community scale differences in pheno-stage probably contribute most to the spectral-spatial phenology. The community-scale mosaic of different pheno-stages will vary according to microclimatic, topographical, pedological, and hydro-meteorological conditions. Each community may have a distinct phenology which may be lagged, ahead of, and sometimes opposed to the general spectral phenology. Unfortunately this explanation does not resolve why such a high correlation exists between canopy openness and MLIV. It is possible that the

#### CHAPTER 7, Understanding Large-Area Phenology

sub-pixel scale processes may provide a explanation. For example, the fall of any large forest tree or branch will reduce canopy leaf area. It will also produce abrupt changes in the local microenvironment (section 2.2.4). In particular, reflectance from these areas will be dramatically changed in quantity and also altered in spectral quality (with a shift to greater visible reflectance and less in the NIR wavelengths). With this increase in total EMR received at the ground, soil temperatures will increase and the diurnal water and temperature cycles will be amplified (Canham, 1988; Chazdon and Fletcher, 1984a; Chazdon and Fetcher, 1984b). The result will be differences in: microclimate; the species present (the ratio of dicotyledon to monocotyledon plants); the ratios of pinnate to palmate leaves; and resultant photosynthetic pigment and cell structural contrasts (see Chapters 2 and 5; and Dantas and Muller, 1979). The overall effect will be that the phenological character of such areas will be substantially different to that of the adjacent TF canopy.

Variations in canopy density  $(\tau)$ , contagion and / or shadowing will also accompany changes in canopy leaf area. These variations will also have a strong seasonal (phenological) dimensions. For example, in the austral dry winter season the lower canopy LAI will lead to the TF being more heterogeneous. A greater gap reflectance contribution along with associated shadowing will be present therefore in the integrated signal. In the austral winter gap and ground reflectance contributions along with the implied shadowing will be minimal.

## 7.2.3.2 Las Trancas (Savanna Aborizada)

At Las Trancas, four measures of biological phenology were regressed against the monthly composite MLIV ( $+/-30^{\circ}$  from nadir). The results are shown in table 7.10.

Untemporan	cousy
MLIV (±30° Nadir)	
Correlation Coefficient (r)	**Indicates 99% Significance
0.729	
0.535	
0.685₩	
0.634₩	
0.693₩	
	MLIV           (±30° Nadir)           Correlation           Coefficient (r)           0.729           0.535           0.685☆           0.634季           0.693季

Table 7.10 Regression and correlations obtained between MLIV and ground observations: Savanna Aborizada Las Trancas Lag 0(Contemporaneous)

#### CHAPTER 7, Understanding Large-Area Phenology

All three ARS measurements produced significant correlations with the spectral-spatial phenology, whilst canopy openness produced a high but insignificant association (at the 90 %). These results are unsurprising since canopy trees comprising between 5 and 15 percent of the projected ground area. They are not therefore the dominant vegetation type at this site. Any changes in canopy openness will have only a very limited effect on the spectral-spatial phenology in this landscape.

At a 2-3 km<sup>2</sup> scale, changes in spatial pattern associated with monocotyledon seasonal development (e.g. the contribution of shadows to the integrated signal) is probably the most important single factor in determining local variance changes. However, many different spatially referenced environmental parameters can be invoked as potential sources of variations in phenology. For example, variations in:

- (i) the availability of water;
- (ii) size of forest islands;
- (iii) thickness of the soil;
- (iv) anthropogenic factors such as grazing points for local cattle;

would all cause pheno-stage variations in the savanna communities, and so potentially influence MLIV. Further, all these factors may interact in a complex manner to determine the VI texture at any one time.

#### 7.2.3.3 Seasonally-inundated tropical forest

At Chapare, five measures of biological phenology were regressed against the monthly composite MLIV ( $+/-30^{\circ}$  nadir).

hapare I	Lag 0(Co	ntemporaneo	ous)
		MLIV (±30° Nadir)	
		Spearman's rho	
Total	Litter	0.346	
Leaf I	litter	0.507	]
Derive	d LAI	0.659	
Canopy C	<b>)</b> penness	0.877**	
ARS G	round	0.767*	

✤Indicates 90% Significance
\*Indicates 95% Significance
\*\*Indicates 99% Significance

Changes in the spatial structure of the local environment image were significantly correlated with two of the five measures of biological phenology. Canopy openness again produced the most significant association. Again, this may result from community level variations in pheno-stage (particularly in the leveé zone where inundation affects are greatest, plate 3.3) and / or the seasonally variant reflectance contribution from the ground and understorey strata.

## 7.2.4 Factor-based models

The second method used to analyse the relationship between spectral and biological phenology was based on factor analysis. Several different factor extraction methods were experimented with namely:

(i) Principal Components Transformation. This linear co-ordinate rotation converts m correlated dimensions into n independent (uncorrelated) dimensions where  $m \ge n$ . The first component represents maximum variance. Successive components explain progressively smaller portions of the variance that are uncorrelated with each other. In 2-dimensions:

$$P_{e} = \sum_{k=1}^{n} d_{k} E_{ke}$$
 [7.4]

Where:

e is the number of the principal component,

Pe is the output principal component value for principal component band e,

k is a particular input date,

n is the total number of input dates,

d<sub>k</sub> an input data value for date k, and

E the eigen vector matrix,  $E_{ke}$  being the element of that matrix at row k column e.

- (ii) Unweighted Least-Squares. This is a factor extraction method that minimises the sum of the squared differences.
- (iii) Weighted Least-Squares. This is a factor extraction method that minimises the sum of the squared differences and correlations are weighted by the inverse of their uniqueness, so that variables with high uniqueness are given less weight than those with low uniqueness.

(iv) Maximum Likelihood. This is a factor extraction method that produces parameter estimates that are most likely to have produced the observed correlation matrix if the sample is from a multivariate normal distribution. The correlations are weighted by the inverse of the uniqueness of the variables, and an iterative algorithm is employed.

When applied to the data, all four methods produced similar results. The principal components technique was therefore selected since the derived factors are uncorrelated with one another.

Initially the five measures of biological phenology: total litterfall<sup>1</sup>; leaffall<sup>1</sup>; derived LAI<sup>1</sup>; canopy openness; and ARS measurements were transformed using principal components. The first principal component exhibited the largest sinusoidal seasonal variance (figure 7.26) and was therefore taken to represent the biological-phenological activity at each site.

Principal component transformations of the adjacent area (225km<sup>2</sup>) SAVI images were then calculated (Townshend *et al.*, 1985) figure 7.27 (Lomerio); figure 7.28 (Las Trancas); figure 7.29 (Chapare). PC1 was interpreted as albedo and PC2 as the seasonal change in vegetation (spectral phenology).

The first principal component of biological phenology was then tested for associations with: (i) SAVI (+/-  $30^{\circ}$  from nadir); (ii) MLIV (+/-  $30^{\circ}$  from nadir), and (iii) PC2 (+/-  $30^{\circ}$  from nadir) using the methodology described in section 5.2.1. Correlations were calculated for contemporaneous observations only since spectral reflectance is an instantaneous process.

## 7.2.4.1 Lomerio (seasonal semi-deciduous tropical forest)

Figure 7.26 plots the seasonal variance in the first principal component of the five biological phenological parameters at Lomerio. PC1 steadily rises from July onwards to reach a maximum in January. A slow and steady decline is then evident during the austral autumn. In general, this curve represents well the biological phenology outlined in Chapter 5.

On correlating the three spectral phenological indices (SAVI; MLIV and PC2) against the ground verification PC1, Table 7.12, only the SAVI (+/- 30° nadir) produced a significant association. This indicates that spectral vegetation indices represent an most effective method of monitoring vegetation phenology using remote sensing at this site.

<sup>&</sup>lt;sup>1</sup> Used at the Seasonal semi-deciduous TF and seasonally-inundated TF sites only

Lomerio	SAVI (+/- 30-Degrees Nadir)	MLIV	PC2			
PC1 -Ground Monitored Phenology	0.77*	0.728	0.734			
	포] *] **	ndicates 90 ndicates 95 Indicates 99	% Significa % Significa % Significa			

## Table 7.12 PC1 biological phenology vs. spectral phenological variables: Lomerio (seasonal semi-deciduous TF)

# 7.2.4.2 Las Trancas (Savanna Aborizada)

Figure 7.26 plots the seasonal variance in the first principal component of the five biological phenological parameters at Las Trancas. PC1 again rises steadily from July onwards to reach a maximum in January. A slow and steady decline is then evident during the austral autumn. In general, this curve represents well the biological phenology outlined in Chapter 5.

Table 7.13 PC1 biological phenology vs. spectral phenological variables:

Las Trancas (2	Savanna Adorizada)			
Las Trancas	SAVI (+/- 30-Degrees Nadir)	MLIV	PC2	
PC1 -Ground Monitored Phenology	0.918**	-0.667	0.697	
	र्स् *] **	Indicates 90 Indicates 95 Indicates 99	% Signific % Signific % Signific	cance cance cance

On regressing the three spectral phenological indices (SAVI; MLIV and PC2) against the ground verification PC1, Table 7.13, again only the SAVI (+/- 30 ° nadir) produced a highly significant association. The other two spectral phenologies failed to produce significant associations again. Again, spectral vegetation indices may again represent the most effective and representative method of monitoring vegetation phenology using remote sensing at this site.

# 7.2.4.3 Chapare (seasonally-inundated tropical forest)

Figure 7.26 shows the seasonal variance in the first principal component of the five biological phenological parameters at Chapare. PC1 curve phase is in general agreement with the curves for the other two verification sites, its seasonal variance is greatest.

Chapare	SAVI (+/- 30-Degrees Nadii	) MLIV	<b>PC2</b> -0.081	
PC1 -Ground Monitored Phenology	-0.334	-0.7		
- 208	s-	Indicates 96 #Indicates 95 #Indicates 95 #*Indicates 9	0% Signifi 5% Signifi 9% Signif	icance icance ficance

Table 7.14 PC1	<b>Biological Ph</b>	enology vs.	. Spectral	Phenological	Variables
	Chapare (s	seasonally-i	nundated	TF)	

On correlating the three spectral phenological indices (SAVI; MLIV & PC2) (using Spearman's rho) against the ground verification PC1, Table 7.14, no significant associations were obtained. The general lack of correlation between the PCs probably results from aseasonal nature of both the spectral and biological phenological datasets.

#### 7.3 SUMMARY

Spectral phenological changes have a strong physiological and biological basis at two of the monitored TF sites, the seasonal semi-deciduous TF and the Savanna Aborizada. At Lomerio, spectral phenology showed significant statistical associations with the degree of canopy openness, derived LAI and ARS ground reflectance measurements. The monitoring of just one of these biological indices may be enough therefore to characterise the relationship between spectral and biological phenology at this TF formation. At Las Trancas (Savanna Aborizada) a spectral phenology highly correlated with automated reflectance measurements was revealed. However, in the more complex multi-successional and less seasonal TF formation at Chapare most phenological monitoring procedures failed to produce significant associations with spectral phenology.

In general, the associations between ground verification data and spectral-spatial phenological monitoring were slightly less significant than those obtained by spectral (VI) techniques. Spatial-spectral phenological changes are probably the result of community level variations in phenological stage. Such textural phenological variances are most highly correlated with canopy openness. This may indicate that the MLIV technique is sensitive to changes in the spatial mosaic which result from:

- (a) variations in the ground-reflectance contribution to the integrated reflectance; and
- (b) canopy variations in density, contagion and shadowing.

Both these variations have a seasonal (phenological) component. This explains why significant correlations were established for the Lomerio site but not for the Las Trancas site (where trees are not the dominant vegetation form).

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# CHAPTER 8 CONCLUSIONS

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# CHAPTER 8 CONCLUSIONS

The nature of a PhD investigation is that it is finite; geographical exploration and research, however, tend towards the infinite. As a result, this thesis represents a series of compromises. It was a monumental task to remain focussed when so many possibilities for investigation kept arising. The research experience being best described as fractal. Each time a research topic was concluded; new investigative avenues seemed to have arisen and the task multiplied. Some of these are listed, for future research, in section 8.2.1. However, the thesis title 'Understanding large area phenology' remained constant throughout, as did the core aim of exploring the relationship between biological and spectral phenology in tropical ecosystems.

In this chapter, the research findings of this thesis are summarised. The conclusions are restated (section 8.1) and recommendations for future research suggested (section 8.2). Finally, this investigation is placed in the wider context of the degradation of tropical forest and humid savanna biomes (section 8.3).

## 8.1 SUMMARY OF RESEARCH FINDINGS

Since the aim of this study was to explore the relationship between biological and spectral phenology, and thereby deepen the understanding of large-area TF phenological processes, the research findings are summarised in three sections: biological phenology (section 8.1.1); spectral phenology (section 8.1.2); and large-area TF phenology (section 8.1.3). These conclusions are analysed as site specific level summaries and at a more general ecosystem level.

The specific research objectives were (cf. section 1.3):

- (i) to establish a protocol for monitoring the biological phenology and meteorological seasonality at a large area spatial scale (sections 8.2.1 and 8.2.1.1);
- (ii) to determine the spectral phenology at each field verification site (section 8.1.2);
- (iii) to determine the relative importance of the different environmental triggers at each field verification site (section 8.1.1; 8.1.2 and 8.1.3);
- (iv) to ascertain which of the biological phenologies at the field verification sites can accurately be characterised by a spectral phenology (section 8.1.3); and

 (v) to investigate the relationships between spectral-spatial changes in the satellite image data and the biological phenological changes observed at the filed verification sites. (section 8.1.3).

## 8.1.1 Biological phenology

The three vegetation communities, monitored in this study, were selected since they each represent a distinct point on the Western Amazonian continuum of vegetation seasonality (cf. Chapter 2). The degree of deciduousness, the synchronisation of leaf fall (and other phenological events) with climate was therefore expected to increase from the field verification site at Chapare (the most evergreen) through to Las Trancas field verification site (the most seasonal). These expectations were met in the main with most phenological monitoring techniques recording increases in seasonality along the gradient.

## Las Trancas (Savanna Aborizada)

At Las Trancas, the Savanna Aborizada field verification site, highly significant associations were evident between meteorological parameters (especially those including hydrological terms) and the biological phenological observations (Table 8.1). This coupling between climate and vegetation was particularly evident in the ground stratum where the whole plant phenology of monocotyledons was very dynamic and dominated by a strong seasonal element. The tree stratum leaf-phenology was more conservative and characterised by a more moderate seasonality.

The natural phenological cycle, at this site, is modified by a strong anthropagenic input. Fires are set annually, at the end of the dry season, to enhance the annual flush of ground vegetation for cattle forage. The result is a sub-climax managed landscape mosaic with many different vegetation successional stages represented.

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Table 8.1 Summary of the statistical associations at Las Trancas (the Savanna Aborizada)

	Temperature	Precipitation	Relative Humidity	Evaporation	<b>Canopy</b> openness	ARS ground-1	ARS ground-2	ARS tree	SAVI (±30° nadir)	MLIV (±30° nadir)
Temperature										
Precipitation	х				172					No. and
Relative Humidity	х	х				1				
Evaporation	х	х	х							
Canopy openness	+1	+1	0	0		11 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1				
ARS ground-1	-1	0	0	0	х					
ARS ground-2	-1	0	0	0	х	99%				
ARS tree	-1	0	0	0	х	99%	99%			
SAVI (±30° nadir)	-1	-1	0	0	99%	99%	99%	99%		
MLIV (±30° nadir)	-2	-1	-1	-1	ns	90%	90%	90%	95%	

0 association most significant contemporaneously

-1 association most significant at lag -1 month

+1 association most significant at lag +1 month

X not calculated

ns no significant association

contemporaneous association significant at (%)

# Lomerio (seasonal semi-deciduous tropical forest)

At Lomerio, the seasonal semi-deciduous tropical forest field site, high significant associations between meteorological variations and biological phenological parameters were recorded (see Table 8.2). Changes in humidity and potential evaporation appear to be particularly significant phenological triggers. At the community (large-area) level, a leaf phenology consistent with a vegetation community highly adapted to a seasonal water deficit was noted, i.e. in the driest months evapotranspirational losses are minimised by reductions in leaf area. Canopy trees are the most seasonal vegetation elements. This is probably due to the microclimate (of the canopy stratum) being the most seasonally variant of all the strata in the

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forest. In the more stable (humid) microclimate, of the ground and understorey stratum, PAR may be the limiting growth factor. Reductions in canopy density may therefore provoke localised leaf flushing episodes. In general, however these lower strata are more evergreen.

Across the forest concession, microclimatic variations dictated a diversity of modifications to this general pattern.

	Temperature	Precipitation	Relative Humidity	Evaporation	Litterfall	Leaf fall	LAI	Canopy openness	ARS ground	SAVI (±30° nadir)	MLIV (±30° nadir)
Temperature											1
Precipitation	х						1.5%		100		11
Relative Humidity	х	х					1334				1
Evaporation	Х	х	х			-					
Litterfall	-1	+1	+1	+1						13.	
Leaf fall	-1	+1	+1	+1	99%						
LAI	1	0	0	0	х	х				12.20	

X

X

ns

90%

ns

0

0

ns

Х

Х

ns

ns

Х

Х

99%

95%

X

90%

99%

95%

95%

90

%

Table 8.2 Summary	ofthe	statistical	associat	ions at	Lomerio	(seasonal	semi-	deciduous	TF)

0 association most significant contemporaneously

-1 association most significant at lag -1 month

0

-1

ns

0

0

0

-1

0

1

0

-1

0

0

ns

+1 association most significant at lag +1 month

X not calculated

Canopy

openness

**ARS** ground

SAVI

(±30° nadir) MLIV

 $(\pm 30^{\circ} \text{ nadir})$ 

ns no significant association

contemporaneous association significant at (%)

## Chapare (seasonally-inundated tropical forest).

The seasonally inundated tropical forest, at the field verification site in Chapare, was expected to exhibit the least seasonality, and indeed minimal statistical associations were recorded for this site (Table 8.3). However, a minimal dry season deciduousness was complemented by a leaf fall event associated with a period of inundation. This is probably a consequence of anaerobic conditions in the rooting zone. The degree of phenological synchronisation across the field site was low however. Generally, the recorded biological phenological measurements had a much lower degree of association with the meteorological variables than at the other two sites. This lack of community phenology was attributed to the availability of water throughout the year.

	Temperature	Precipitation	Relative Humidity	Evaporation	Litterfall	Leaffall	LAI	Canopy openness	ARS ground	SAVI (±30° nadir)	MLIV (±30° nadir)
Temperature					A. S.						14
Precipitation	X									-7175	
Relative Humidity	x	x									
Evaporation	x	x	Х								
Litterfall	Ns	ns	ns	ns							
Leaf fall	ns	ns	ns	ns	95%						
LAI	0	ns	ns	ns	X	Х					
Canopy openness	ns	0	ns	ns	X	Х	Х				
ARS ground	ns	+1	ns	ns	X	Х	Х	Х			
SAVI (±30° nadir)	ns	ns	ns	ns	ns	ns	ns	ns	95%		
MLIV (±30° nadir)	ns	-1	- 1	ns	ns	ns	ns	99%	95%	90 %	

Table 8.3 Summary of the statistical associations at the Chapare (seasonally-inundated TF)

association most significant contemporaneously 0

association most significant at lag -1 month -1

association most significant at lag +1 month +1

not calculated X

no significant association ns

contemporaneous association significant at (%)

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#### General:

Linking a distinct phenological phase to a particular environmental trigger was difficult for a number of reasons. Firstly, phenological phases represent a time integration of many abiotic and antecedent biotic conditions preceding the observation / measurement. Secondly, in these heterogeneous tropical vegetation formations the phenological phases of different plants overlap one another and multiple pheno-stages are often evident simultaneously. The rôle of meteorological factors appears to be indirect in controlling phenological stage. In particular, environmental changes that affect soil and vegetation water status stimulate endodynamic processes that control the timing of phenological events and thus synchronise vegetation development with the most optimal seasonal climate. Leaf deployment and abscission are best conceptualised then as a resource allocation processes. In this scenario, the best use of the abiotic resources available within (or anticipated by) each stratum at a particular point in time will always be found.

## 8.1.2 Spectral phenology

The three verification sites were expected to yield increasing seasonality in their spectral phenologies from Chapare (the least seasonal) to Las Trancas (the most seasonal). This was the case, with all spectral phenological techniques used being in agreement. At the Lomerio and Las Trancas no differences were noted between the single pixel and adjacent area spectral phenologies. At Chapare (the seasonally-inundated TF site) a difference was noted but attributed to the different monitoring scheme used.

## Las Trancas (Savanna Aborizada).

On the basis of spectral phenology alone, this verification site would be difficult to distinguish from the Lomerio (seasonal semi-deciduous tropical forest) verification site. Only in the dry, austral winter, season when Las Trancas is characterised by a greater variance (standard deviation) of recorded reflectance values and slightly lower VI values was discrimination possible.

# Lomerio (seasonal semi-deciduous tropical forest)

Characterising this site using a spectral phenology alone, a single (substantial) reduction in photosynthetic activity during the drier winter period (June-September) would be detected. Again, the potential for confusion between this site (seasonal semi-deciduous tropical forest) and the Las Trancas (Savanna Aborizada) is great.

# Chapare (Seasonally Inundated Tropical Forest).

At this field verification site, single pixel and adjacent-area spectral phenologies were substantially different. Using the adjacent area (225 pixel) monitoring scheme alone, a moderate reduction in photosynthetic activity, during the slightly drier winter period (July-August), would have been recorded. However, single pixel monitoring revealed two-phases of reduced photosynthetic activity, the first in the drier austral winter and the second associated with the wetter summer season. These differences were caused primarily by the loss of some images (due to cloud) from the adjacent area monitoring scheme.

#### General:

All three verification sites produced spectral phenologies in line with the increasing seasonality anticipated by their position on the vegetation continuum. Few effects due to differing view geometries were noted; indeed the temporal resolution of observation seemed far more important in characterising TF phenology. The major limiting factor on the number of useful image-dates was the incidence of clouds rather than the repeat cycle of the satellite-sensor combinations.

# 8.1.3 Large area tropical forest phenology Lomerio (seasonal semi-deciduous tropical forest)

At Lomerio, the biological phenology of the canopy varies in general accordance with the spectral phenology. However, the understorey and ground strata have a more evergreen biological phenology. Their reflectance signal will be integrated within the general remotely-sensed spectral phenology. Since the upper and lower strata may have opposed phenological cycles for some of the year (i.e. when the canopy is bare and the ground vegetation is photosynthetically active) the true degree of seasonality in the canopy is likely to be under-

represented in the spectral phenologies. The connections between spectral and biological phenologies are relatively straightforward.

- (i) When the TF canopy is at its most dense, spectral phenology is dominated by reflectance from the canopy.
- (ii) As the canopy thins, the understorey and ground vegetation components, along with shadowing and substrate components, contribute a greater part of the integrated reflectance signal.
- (iii) Since the understorey and ground vegetation strata are more evergreen than the canopy, the integrated seasonality of the spectral phenology of the forest is attenuated.

## Las Trancas (Savanna Aborizada)

In contrast to Lomerio, at the Savanna site the strata contributions to spectral phenology are reversed. In the wet austral summer, monocotyledon-dominated ground vegetation dominates spectral reflectance. In the drier austral winter, this component of the ground vegetation is almost absent, soil dominates integrated reflectance, and the less seasonal savanna trees become the most important vegetative reflectance components.

In the austral summer, the spectral phenologies of Lomerio and Las Trancas are almost identical, yet their biological phenologies are very different. During this season the canopy vegetation at Lomerio dominated the integrated reflectance pattern, whilst at Las Trancas the monocotyledon-dominated ground vegetation is the major component of the reflectance signal. Classification of these two vegetation classes based purely on spectral phenology could clearly be erroneous.

# Chapare (Seasonally Inundated Tropical Forest)

At Chapare, flushing and leaf fall amongst the canopy trees was not well synchronised, either with climate or with each other. This precipitates in an integrated spectral effect that does not include large contributions from the ground or understorey strata. The net affect is to produce a semi-evergreen spectral phenology (i.e. one where the canopy component in the integrated signal is stable). It should be noted however, that 1995 and 1996 were dry years and the wet season litterfall may typically be much greater.

## General

Biological phenology is a complex adaptation to a seasonally-varying climate. Since meteorological variables are highly spatially and temporally variant, it is not surprising to find that different biological phenologies exist. In any complex vegetation community, these different phenological stages will be superimposed on each other in the following ways.

- (i) In general, the degree of synchronisation of leaf fall in tropical vegetation will increase as the hydro-meteorological conditions become more seasonal.
- (ii) However, since the water status of leaves in canopy trees is more seasonal than that of leaves of the lower strata vegetation, the leaf fall strategy of canopy trees will be more synchronised and seasonal.
- (iii) As the canopy opens, due to leaf fall, the ground vegetation may flush, or at least remain photosynthetically active, to exploit the more moderate microclimate.
- (iv) At the wetter end of the tropical forest continuum, inundation and the resulting anaerobic soil conditions may be the main controls on litterfall.

At the large-area  $(1 \text{km}^2)$  remotely sensed scale, any of these biological phenologies may be integrated in each pixel. The more complex and heterogeneous the vegetation type the greater the degree of integration and the less clear the seasonal spectral curve. In the Savanna Aborizada the structure is simpler than in the seasonal semi-deciduous TF and this in turn is simpler than the seasonally inundated TF (Figure 8.2).

Interpretation of the exact nature of these spectral phenological changes is difficult since the scale of observation is artificially imposed and has no natural definition (e.g. leaf-scale, or tree-scale). Complex ground parameters clearly better describe spectral phenology and this has implications for determining the biological significance of spectral phenology since it still remains for the researcher to determine what changes in parameters, such as canopy openness or ARS-reflectance, mean biologically. In two of the monitored tropical vegetation formations spectral phenology was shown to have a strong physiological basis at the scale of the vegetation community. At the third site, the seasonally-inundated TF, the results were less conclusive. These findings have important implications for mapping and monitoring vegetation using 1km resolution satellite data. In vegetation communities that are relatively simple (in terms of their structure and floristics i.e. species diversity) seasonal trends in spectral curves are clearly indicative of plant physiological processes at a community level. Previously, this has been assumed, based on the 'leaf-scale' analysis of spectral responses to environmental stresses. This research has proven that this relationship holds true for vegetation communities with a strong seasonality and provides a verifiable basis for spectral

#### **CHAPTER 8, Conclusions**

phenology to be related to a holistic view of ecosystem-scale responses (rather than leaf-scale) to abiotic and biotic parameters. It is possible to infer from this that other ecosystems exhibiting strong seasonality can be investigated successfully using a spectral phenology. On the basis of these results, the slightly drier tropical environments, such as the structurallysimple grass-dominated savannas and chaco vegetation formations, are being successfully monitored (Figure 8.1). Similarly, in marginally wetter environments (e.g. seasonal deciduous or monsoon forests, Figure 8.1), it may be possible to monitor forests which are structurally and floristically more complex, with a high degree of confidence being placed in spectral phenological observations. However, the ability to monitor very structurally complex, heterogeneous and / or humid tropical forests, has not been demonstrated, within this study. Some seasonal trends in the seasonally-inundated tropical forest canopy were borne out by the spectral data, but in other cases they were not. Moreover, the results varied with spatial scale. The single-pixel scale providing more confusing results than the analysis of the local image variance derived from a wider area. It should be noted however that these results were acquired from a lone humid TF site and can not be extrapolated all encompass all terra firme forest areas. Clearly, further work is required before the scientific community can be certain that all temporal trends, derived from 1km spatial resolution image data, are providing accurate insights into biological processes, of humid tropical forests, but in general the association between spectral and biological phenology is strong.

# **8.2 RECOMMENDATIONS FOR FUTURE WORK**

# 8.2.1 Research agenda

In this section, some suggestions for improvements to the techniques used in this investigation are proposed. First, the ground verification procedures are evaluated (section 8.2.1.1) and second, the conceptual and instrumentation advances within EO science likely to be useful in large area phenological research are outlined (section 8.2.1.2).

### 8.2.1.1 Ground verification

Many improvements to the ground verification methodology are possible. Principal amongst these must be a strata-specific meteorological parameterisation. This is needed in order to understand the exact nature of the botanical-phenological responses in different TF strata. This instrumentation must be able to monitor a parameter without inherently changing it and sample a sufficient spatial distribution to allow extrapolation over large heterogeneous areas. The monitoring of biological phenology could also be stratified in a similar manner by sampling vertically through the canopy and by acquiring the following data for each stratum:

- (i) canopy openness,
- (ii) litterfall losses,
- (iii) LAI estimations, and
- (iv) measured reflectance-values.

Again, a much larger number of sampling points would facilitate large-area extrapolation. Litterfall monitoring in particular would benefit from: (a) increases in sampling area by several orders of magnitude; as well as (b) the quantification of basket losses due to litter blow and decomposition. The direct phenological observations could be standardised by the use of reference photographs.

The ARS was not intended to be a precision instrument since its purpose was to give an indication only of reflectance changes in the TF. However, several improvements could be made to the system.

(i) Spectral and radiometric resolutions could be increased. These would allow for the detection of more subtle spectral changes (i.e. red edge shifts). However, it would necessitate the use of the more expensive defraction-grating technology rather than the gelatine filters used in this study. This would be hard to justify, from either a financial, logistical or scientific stand-point, since the structural complexities and implied integrated reflectances, that occur even within a diode FOV, would swamp the subtle spectral changes a defraction-grating based radiometry system could detect.

- (ii) Monitoring the integrated reflectance of far larger landscape mosaics, i.e. at a spatial scale of 10m<sup>2</sup> 100m<sup>2</sup>. This last FOV would necessitate the use of tethered balloons (see Appendix 3.9).
- (iii) Monitoring multiple points of the bi-directional reflectance using a system of fibre optics (Appendix 3.9).
- (iv) Increases in the spatial sample, i.e. the use of a far greater number of diodes until a reasonable F statistic was obtained. This would allow the spatial auto-correlation to be established for each stratum. On a more practical note, great care should be taken with sensor / instrument placement. Particularly, areas near the 'azteca' tree, *Cecropia yganus*, whose hollowed out internodes are inhabited by an extremely unpleasant species of ant.
- (v) The scale of sampling in relation to the scale of pattern in the community requires fuller consideration (Greig-Smith, 1964). The patterns and gradients within tropical vegetation communities are on a relatively large scale compared to the observer.

Additional botanical, abiotic and environmental parameters that would enhance any further large area tropical phenological study include: soil moisture data as well as a better quantification of the total biomass changes in the ground stratum (particularly in a savanna environment).

## 8.2.1.2 Remote sensing

A high temporal frequency and good seasonal distribution of images for analysis is of paramount importance in spectral phenological studies (Wellens, 1997; Millington *et al.*, 1992; 1994). Any spatial, radiometric or spectral improvements should not sacrifice temporal resolution. Furthermore, a true temporal resolution should be attained, i.e. one with a high directional fidelity where observations have a similar view geometry. Of primary concern is the elimination of the extreme look angles obtained by sensors with extremely large swath widths (e.g. AVHRR). The matter of temporal resolution aside, a number of interesting advances are on the horizon in EO science which have potential for phenological studies. Firstly, hyperspectral remote sensing systems are starting to become available (e.g. the 192 band High Resolution Imaging Spectrometer, HIRIS) and may eventually have high temporal resolution global coverages. These will allow the more accurate parameterisation of spectral shifts in vegetative reflectance. The monitoring of changes in the position of the red-edge, for example, has been associated with forest senescence and other phenological changes (Collins,

1978; Horler and Barber, 1981; Miller *et al.*, 1991; Baret *et al.*, 1992; Baret *et al.*, 1994). The MODIS sensor, mounted on board the EOS -am and pm platforms (to be launched 1998 and 2000 respectively) will possess 36 spectral bands (2 at 250m; 5 at 500m 29 at 1000m) many at useful wavelengths for the detection of cell pigment and cell structural changes. Other important research areas include the development of spatial-temporal analysis techniques (such as mean local image variance) which exploit the dynamics of landscape contagion, entropy and pattern. These have been correlated with biological phenological parameters in this study. Unfortunately, no extrapolation of spatial variance analysis to composite images, i.e. GAC and 1-degree GVI etc. is possible since only contemporaneously acquired imagery with similar view geometry is suitable.

Cecchi *et al.* (1994) and Méthy *et al.* (1994) both comment on the use of a fluorescence lidar system (a laser system, telescope, spectrometer and diode array) sensitive in the ultra violate wavelengths where most organic molecules have a strong absorption feature. The choice is restricted to the near UV because of low atmospheric transmission below 300nm.

There are good reasons to expect data from optical sensors to be more effective when combined with data from active sensors, such as radar (Radambrasil, 1978; Aschbacher, 1991; Israelsson, 1994; Keil, 1994; Long *et al.*, 1994). In the future, time-series of microwave, thermal and optical data will provide new synergies to probe the complexities of TF ecosystem phenology. Lastly, statistical modelling of the relationships between spectral and biological phenology could be undertaken with the aid of even more comprehensive data bases. Further, Ekstrand (1994); Gao and Goetz (1994) have all proposed the use of non-linear models in phenological studies. Although such models are not suggested by the scatterpolts (figures 7.13-7.24) linear regressions might not always be appropriate since there may be measurement errors associated with both the ground and remotely sensed data.

#### **8.3 EPILOGUE**

The body of scientific knowledge concerning the botany, ecosystem dynamics and phenology of tropical forests is incomplete. This is particularly true of neotropical tropical vegetation. In spite of our ignorance, tropical forests are being degraded and destroyed at perhaps the highest rates known in world history. Some of the very many recent estimates conclude that between 140,000 km<sup>2</sup> and 200,000 km<sup>2</sup> of TF are being cleared annually for agriculture, timber extraction, ranching, mining, infrastructure developments and land speculation (Houghton, 1990; Blasco and Achard, 1990; Myers, 1989). These current rates of exploitation (if continued) will result in the nearly complete loss of the extant tropical forests, for much of the world, over the next few decades. In some tropical countries, such as Haiti, which were formerly rich in tropical forests, this has already occurred. The detrimental impact of such extensive TF destruction on rural communities, biodiversity, aquifer recharge, and through tele-connections on global climates, cannot be ignored. Tropical forests represent a major store of terrestrial carbon. Changes in forest area or density will impact on the global carbon cycle and so potentially on the global climate (Stoms and Estes, 1993; Curran et al., 1996). Strong scientific imperatives also exist to preserve the high species diversity of these ecosystems. It has been estimated that, more than 3 million animal species live in humid TF ecosystems (1.7 million species having already been recorded for the Amazon basin alone, Terborgh, 1985). Other authors estimate that the global total of TF species may be as high as 30 million (e.g. Erwin, 1988). Primary humid TFs may then account for between one-half and two-thirds of the world's gene pool (being rivalled only by coral reefs in terms of species richness), their diversity of avifauna and arboreal invertebrates being particularly great (Longman and Jeník, 1987; Reading et al., 1995). Future medicinal and scientific advances, based on these species, may then be nullified or impeded without swift conservatory interventions (Sader et al., 1990). Finally, there is a strong emotional case for the preservation of TFs purely for their intrinsic worth. These incompletely understood, mysterious and incredible vegetation assemblages form part of our global heritage. Their biodiversity is intimately interconnected with the long-term health and vigour of the biosphere, including its more densely populated non-tropical areas.

All of the sites monitored within this investigation are threatened in some way. The seasonally inundated TF site, in Chapare, has the guardianship of being a reserve of a public university. The protection this status affords stops serious, but not minor encroachments. This

#### **CHAPTER 8, Conclusions**

occurs since the site has the misfortune to be surrounded by an increasingly settled human landscape with many poor migrants demanding land to subsist and to supply the international demand for cocaine. Observation of figure 3.3 will demonstrate that this reserve is now functionally isolated and consequently genetic interchange between the forest species of the



Plate 8.1 Tropical forest clearance at the edge of the University concessions, Valle de Sajta, Chapare

reserve and the forests of Beni and Chimore (contiguous Amazonia) is severely compromised.

The Lomerio (seasonal semideciduous TF) site is theoretically owned by the indigenous people of Chiqitania. Unfortunately, they were being encouraged to 'exploit' their 'renewable natural resource' as this research commenced. This harvesting although done with the help and co-operation of the US-AID is (in the opinion of this author) nothing more than oldfashioned forestry dressed-up as sustainable development. Such destruction must be set in the context of the forests of Lomerio being amongst the last semideciduous tropical forests of the Precambrian shield. At present

rates of exploitation, they will be gone by the end of the century (Killeen *et al.*, 1990). So what will take the place of these forests? Their most common fate to date is to become agricultural monocultures or rangelands supporting beef cattle (for international markets). The foreign currency generated from these conversions being more valuable, to a developing economy, than the unique floristic composition of the vegetation. There is an awful inevitability that, the tropical forests of the Bolivian Amazon will all soon form part of the nation's *natural history*, rather than its *natural present*.

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#### Appendix 2,1

SEASONAL

DECIDUOUS FOREST ALLUVTAL UNIFORM CANOPY CANOPY WITH EMERGENTS LOWLANDS UNIFORM CANOPY CANOPY WITH EMERGENTS SUB-MOUNTAIN UNIFORM CANOPY CANOPY WITH EMERGENTS MOUNTAIN UNIFORM CANOPY CANOPY WITH EMERGENTS UPPER-MOUNTAIN UNIFORM CANOPY CANOPY WITH EMERGENTS WHITE SAND FOREST FORESTED WITH PALMS WITHOUT PALMS

ABORIZADA (WITH TREES) GRASSLAND

SAVANNA FORESTED ABORIZADA (WITH TREES)

Park

GRASSLAND

SAVANNA STEPPE FORESTED ABORIZADA

STEPPE

PIONEER FORMATIONS ECOLOGICAL ZONES OF TRANSITION

(WITH TREES) PARK

GRASSLAND

ABORIZADA

Park

GRASSLAND

WITHOUT GALLERY FOREST WITH GALLERY FOREST

(WITH TREES) WITHOUT GALLERY FOREST WITH GALLERY FOREST

WITHOUT GALLERY FOREST

WITH PALMS

WITHOUT PALMS

WITHOUT PALMS

WITHOUT GALLERY FOREST WITH GALLERY FOREST

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WITH GALLERY FOREST

WITHOUT GALLERY FOREST WITH GALLERY FOREST

#### SOUTH AMERICAN VEGETATION CLASSIFICATION

ECOLOGICAL NICHES OR VEGETATION TYPES

DENSE RAIN FOREST

ALLUVIAL

LOWLANDS

CANOPY WITH EMERGENTS SUB-MOUNTAIN

> UNIFORM CANOPY CANOPY WITH EMERGENTS

AFTER VELOSO

ET. AL. (1991)

UNIFORM CANOPY CANOPY WITH EMERGENTS

UNIFORM CANOPY CANOPY WITH EMERGENTS

UNIFORM CANOPY

CANOPY WITH EMERGENTS

UNIFORM CANOPY

WITH PALMS WITH LIANA

WITH PALMS WITH LIANA WITH BAMBOO WITH SOROROCA

WITH PALMS WITH LIANA

ALLUVIAL UPPER-MOUNTAIN

> UNIFORM CANOPY CANOPY WITH ÉMERGENTS

UNIFORM CANOPY

CANOPY WITH EMERGENTS

UNIFORM CANOPY CANOPY WITH EMERGENTS

UNIFORM CANOPY CANOPY WITH EMERGENTS

UNIFORM CANOPY

MOUNTAIN UPPER-MOUNTAIN

OPEN RAIN FOREST

LOWLANDS

SUB-MOUNTAIN

MOUNTAIN

MIDED RAIN FOREST

SUB-MOUNTAIN MOUNTAIN

SEASONAL SEMI-DECIDUOUS FOREST

ALLUVIAL

LOWLANDS

SUB-MOUNTAIN

MOUNTAIN

UPPER-MOUNTAIN

CANOPY WITH EMERGENTS

## Appendix 2.2



 $AC = OC \tan \alpha 1$ 

## Appendix 2.3

## Calculations of the Solar Zenith (and length of day)

Solar zenith angle ( $\theta$ ), the angle of the sun from the vertical can be calculated from:

 $\cos \theta = \sin (^{)} \sin (\delta) + \cos (^{)} \cos (\delta) \cos (15(T-T_{SN}))$ 

where  $^{=}$  latitude;

 $\delta$  = declination

T = solar time

 $T_{SN} = solar noon$ 

Declination may be estimated from:

 $\delta = -23.5 \cos [360 (D_j + 10) / 365]$ 

where  $D_j$  is the Julian date.

Or,

 $\sin\beta=\cos\theta=\sin\lambda\,\sin\delta+\cos\lambda\,\cos\delta\,\cos h$ 

Where:

 $\beta$  is the solar elevation above the horizontal,

 $\theta$  the zenith angle of the sun (the component of  $\beta$ ),

 $\lambda$  the latitude of the observer,

- $\delta$  is the angle between the sun's rays and the equatorial plane of the earth (solar declination). This a function of the time of year,
- h is the hour angle of the sun (the angular distance from the meridian of the observer) and is given by (t-t<sub>o</sub>) where t is time in hours and t<sub>o</sub> is the time at solar noon. In the western hemisphere, the standard time at local apparent noon is 12.00 - (the equation of time) -4 \* (longitude in degrees).

Month	δ	e			
January	-23.1	-3			
February	-17.3	-14			
March	-8	-13			
April	+4.1	-4			
May	+14.8	+3			
June	+21.9	+2			
July	+23.2	-4			
August	+18.3	-6			
September	+8.6	0			
October	-2.8	+10			
November	-14.1	+16			
December	-21.6	+11			

Solar Declination ( $\delta$ , degree) and the equation of time (e, minutes) on the first day of each month.

For simulation purposes  $\delta$  may be obtained from:

 $\delta = -23.4\cos[360(D_j + 10) / 365]$ 

Where:

D<sub>i</sub> are Julian date (days), Jones (1992); Duggin (1980)

### Appendix 2.4

Heat units are often assumed to control plant growth and development. Units of thermal time are usually expressed as degree days (°Cd), calculated as the sum of the differences between daily mean temperature (T) and the base temperature for each day beyond a given starting date (Snyder, 1985; Ong, 1983).

$$^{0}$$
Cd =  $\sum_{o}^{n} (\overline{T} - \overline{T}_{b})$  for T > T<sub>b</sub>

Where:

 $T_b$  is the threshold temperature

T<sub>o</sub> is the optimum temperature.

Other approaches include calculating a thermal rate (p):

$$p = \xi / (T - T_b)$$

where:

 $\xi$  is the rate of response (e.g. leaf extension mm h<sup>-1</sup>).

### Appendix 3.1

Multi-stage sampling allows inference between large areas of forest inventoried at a general level and smaller plots of forest inventoried in a very detailed survey. An estimate of the first variable is created by utilising its correlation to the second. To execute such a methodology a large sample is initially taken of the first variable (X), e.g. dbh > 30cm. This yields a precise estimate of the population mean or total. Next a sub-sample, is taken from the first stage variable and measurements acquired of parameter (Y), e.g. dbh > 10cm. This process can then be iterated indefinitely. In this way a sub-sample on which both variables (X and Y) have been measured, is created. Using this data, a regression may then be developed between the two variables, and used with the larger sample population (X) to estimate the mean or total of the other variables (Husch *et al.*, 1972).

Total sample inventories are rare (especially in TF environments). Time and cost considerations dictate only a percentage of the total studied area can be surveyed. The selection of the optimum sample plot size is therefore crucial. This should be determined by the spatial distribution and variability of the forest together with the sampling density (constrained by time/cost). Small plots in a homogeneous forest may furnish plots with a high precision, as the number of independent observations per given sampling intensity is great. TFs however are very heterogeneous. The coefficient of variation between small plots may be such that a smaller

number of larger plots (containing more variation) are desirable. Philip (1983) presents a sampling equation to determine the area of plots within a forest inventory.

Where:

a is the area of sampling units,
A the total area of the inventory,
i the intensity of sampling (% of total area),
n the total number of sample units.

In theory, the *sample plot shape* may be any 2-dimensional geometrical object, i.e. a circular, rectangular, square or triangular area. Unbiased estimates can be computed for all shapes. In temperate latitudes, circular plots are common since they have the smallest periphery in relation to area, and consequently the lowest number of borderline trees. In TFs, where access and visibility are difficult, and large areas need to be surveyed, it is more usual to use squares or rectangles as they are easier to demarcate. Borman (1953) and Campbell *et al.*, (1986) showed that elongated rectangular plots (transects) may provide a more accurate analysis of vegetation than an equal number of square plots having the same area. This method was found to be particularly effective when the principal axis of the plot was orientated parallel to the axes of environmental gradients within the area being sampled.

#### Appendix 3.2

In tropical savanna woodlands the nature of the vegetation distribution makes traditional inventory methodology (using static plots) cumbersome. This is because to capture a statistically significant amount of individuals, inventory-plot sizes would have to be huge (commonly many hundreds of metres). Plotless inventories (point-sampling) using a relascope (or angle-gauge) allows the estimation of the basal area of trees, rapidly within large open areas. When held to the eye the relascope provides a fixed gauge angle (a cross-arm of a defined width attached horizontally to a vertically held rod of known length) relative to a datum point. If a tree subtends a smaller angle than the gauge the tree is excluded from the survey; if the tree subtends a larger angle than the gauge the tree is included. Starting at geographical north, all the trees in a 360° sweep are viewed and counted, or not as the case may be. The basal area is determined through multiplication of the number of counted trees by

a constant factor derived from the angle, see Parcel (1993) for a full review of this method. The instrument needs to be calibrated in each new landscape as the basal area per hectare is estimated from the average number of trees counted per sample point multiplied by a factor (f), Hamilton (1975). This factor is derived from a smaller conventional inventory.

# B = 10,000/f2

Within a tropical Savanna an f value of less than 0.5 is appropriate.

e.g. 
$$B = 2500(c/d)^2$$

Where:

**B** is the basal area factor  $(m^2 ha^{-1})$ ,

C the width of the relascope cross piece,

D the distance or length of relascope.

E.g. Cross-arm = 2cm, rod length = 100 cm.

2:100 or 1:50 di:Ri, and Ri = 50 di

All trees with a diameter di with a distance of 50di from the plot centre are registered.

Ri = radius.

Problems associated with method include an assumption in the calculation of a circular survey area when in fact an ellipse (due to landscape factors) is more common (Philip, 1983; Pancel, 1993).

#### **Appendix 3.3**

AWS Automatic Weather Station:	Didcot Instrument Company Ltd.				
Number of Inputs (Campbell Logger)	20				
Output	Digital				
Recorder	Solid State				
Power Supply	Solar & Back-Up Battery				
Weight (Kgs)	80				
Mast Type	Pole / Stacked				
Operating Environment Max (°C)	50				
Operating Environment Min (°C)	-30				

Natural Environment Research Council (Automatic Weather Station Pool), Didcot Instruments Abington, UK, Logged by Campbell CR12 Loggers, Campbell Instruments, Cambridge, UK.

# Appendix 3.4

 $\mathbf{E} = (\rho_{\mathbf{a}} \mathbf{c}_{\mathbf{p}} / \lambda \Upsilon) \mathbf{g}_{\mathbf{l}} \mathbf{e}$ ----

where:

E is the evaporation rate (mm h<sup>-1</sup>)

 $\rho_a dry air density (constant)$ 

 $C_{p}$  the specific heat capacity for air (constant 1012 J kg^{-1} k^{-1})

 $\lambda$  the latent heat of vaporisation(J kg<sup>-1</sup>)

 $\Upsilon$  is the psychrometric constant (equal to 66 Pa ° C<sup>-1</sup>) at sea level in a ventilated psychrometer, (Jones, 1992).

g<sub>l</sub> is the physiological conductance (how easily a surface gives up water), assumed free

Appendix 3.5

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Observation Point	Foliage (1 / 2 / 3 /4)	Flowers Yes or No	<b>Fruit</b> Yes or No
Ground 1			
Ground 2			
Ground 3			
Canopy 1			
Canopy 2			
Strata Sub-Canopy			
Strata Ground			

# TSL260, TSL261, TSL262 IR LIGHT-TO-VOLTAGE OPTICAL SENSORS

Appendix 3.6

SOES008A-DECEMBER 1992 - REVISED FEBRUARY 1993



60° 40° 20° 0° 20° 40° 60° θ – Anguiar Displacement Figure 6 80\*

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# Appendix 3.7 Circuit Diagram of the Automated Radiometry System (Mark-1)



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MV	260- Diode 1		250- Diode1		260- Diode1		250- Diode1		260- Diode1		250- Diode1
0.00015	260- Diode2	0.00029	250- Diode2	0.00029	260- Diode2	0.00011	250- Diode2	0.00009	260- Diode2	0.00024	250- Diode2
0.00018	260- Diode3	0.00019	250- Diode3	0.00028	260- Diode3	0.00016	250- Diode3	0.00013	260- Diode3	0.00029	250- Diode3
0.00009	260- Diode4	0.00028	250- Diode4	0.00022	260- Diode4	0.00019	250- Diode4	0.00004	260- Diode4	0.00021	250- Diode4
0.00011	260- Diode5	0.00028	250- Diode5	0.00021	260- Diode5	0.0002	250- Diode5	0.00015	260- Diode5	0.00036	250- Diode5
0.00012	260- Diode6	0.00022	250- Diode6	0.00029	260- Diode6	0.00034	250- Diode6	0.00019	260- Diode6	0.00031	250- Diode6
0.00017	260- Diode7	0.0003	250- Diode7	0.00035	260- Diode7	0.00026	250- Diode7	0.00022	260- Diode7	0.00012	250- Diode7
0.00001	260- Diode8	0.00021	250- Diode8	0.00041	260- Diode8	0.00027	250- Diode8	0.00004	260- Diode8	0.00019	250- Diode8
0.0002	260- Diode9	0.00017	250- Diode9					0.00016	260- Diode9	0.00025	250- Diode9
0.00017	260- Diode10	0.00017	250- Diode10					0.00011	260- Diode10	0.00029	250- Diode10
0.00016	260- Diode11	0.00022	250- Diode11					0.00009	260- Diode11	0.00016	250- Diode11
0.00014	260- Diode12	0.00028	250- Diode12					0.00024	260- Diode12	0.00016	250- Diode12
0.00021	260- Diode13	0.00019	250- Diode13					0.00019	260- Diode13	0.00026	250- Diode13
0.00014	260- Diode14	0.00014	250- Diode14					0.00011	260- Diode14	0.00018	250- Diode14
0.00011	260- Diode15	0.00037	250- Diode15					0.00007	260- Diode15	0.00032	250- Diode15
0.00013	260- Diode16	0.00024	250- Diode16					0.00019	260- Diode16	0.00022	250- Diode16

**The Logistics of Sensor Placement. Sampling Plans Experimented with;** Fibre Optics and a Transducer array vs. Individual Silicon Phtodiodes






## **Inventory Search Results**

Navigator: Help | Comments | SAA Home Page | NOAA Home Page

#### **AVHRR Section**

	Date		TYPE	SN	[ ]	<u>DUR</u>	]]	DIF	2	Entity ID	1	DIST	OR	<u>D</u>	IMG	I
1.	1995/06/02		1KM	14	.	11		А		AL14060295183541		2		1		
2.	1995/06/03	1	1KM	14	:	12	1	А	I	AL14060395182445		2	l			
3.	1995/06/04		1KM	14	:	12	I	A		AL14060495181348		2	I	l		
4.	1995/06/05	ł	1KM	14	:	11		A	ł	AL14060595180303		2				
5.	1995/06/06	1	1KM	14	:	12	١	A	1	AL14060695175152	1	2			1	
6.	1995/06/07	ł	1KM	14	.	12		A	ļ	AL14060795174054		2	ļ	]	ļ	
7.	1995/06/08	I	1KM	14		12		А		AL14060895172956		2				
8.	1995/06/12		1KM	14	ŀŀ	11	۱	A	I	AL14061295182816		2				
9.	1995/06/13		1KM	14		11		A	ļ	AL14061395181713		2	ł	ł	I	
10.	1995/06/14	ļ	1KM	14	Ŀ	11		A		AL14061495180616		2	I			
11.	1995/06/15	l	1KM	14	L	11		A		AL14061595175518		2	1	I		
12.	1995/06/15	ļ	1KM	14	L	10		A	ł	AL14061595175625		2			ł	
13.	1995/06/16	ł	1KM	14	Ŀ	11	۱	A	ļ	AL14061695174435	l	2	ļ	[	Į	
14.	1995/06/17		1KM	14	1	11		A		AL14061795173324		2	1			
15.	1995/06/21		1KM	14	1	11		A	1	AL14062195183141		2		1		
16.	1995/06/22	I	1KM	14	1	11	I	A		AL14062295182044		2	ł	1		
17.	1995/06/23		1KM	14	1	12	ł	A		AL14062395180955		2		I		
18.	1995/06/24		1KM	14	1	12	١	A		AL14062495175855	1	2		ł	ł	
19.	1995/06/25		1KM	14	1	12	ļ	А	1	AL14062595174752		2	l	l	ļ	

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20.	1995/06/26	1	1KM		14	1	12		Α	Į	AL14062695173655   2	I
21.	1995/06/30		1KM	I	12		4	1	D	1	AL12063095104744   2	1
22.	1995/06/30	I	1KM		14		11	I	A	I	AL14063095183512   2	
23.	1995/07/01		1KM	l	14	Ι	11		A		AL14070195182414   2	
24.	1995/07/02	1	1KM	ļ	14	Ι	11	ł	A	1	AL14070295181313   2	
25.	1995/07/03		1KM	I	14		11	ł	A	I	AL14070395180217   2	l
26.	1995/07/04		1KM	I	14		11		A		AL14070495175118   2	ļ
27.	1995/07/05		1KM	ļ	14		11	۱	A	1	AL14070595174020   2	l
28.	1995/07/10	1	1KM	1	14		10	1	A	ĺ	AL14071095182802   2	ļ
29.	1995/07/12	İ	1KM	ł	14	1	11	1	A	I	AL14071295180540   2	1
30.	1995/07/13	ļ	1KM		14		11	I	A		AL14071395175443   2	1
31.	1995/07/14		1KM	1	12	I	4	I	D	I	AL12071495104324   2	I
32.	1995/07/14		1KM	I	14	I	12	ļ	A	۱	AL14071495174348   2	
33.	1995/07/15		1KM	1	14	I	12	ļ	A	۱	AL14071595173246   2	1
34.	1995/07/19		1KM		14	ł	11		A	I	AL14071995183102   2	
35.	1995/07/20	!	1KM		14		11	ļ	A	I	AL14072095182003   2	ļ
36.	1995/07/21	ļ	1KM	ł	14	I	11	۱	A	ļ	AL14072195180906   2	
37.	1995/07/22		1KM		14		11	I	A		AL14072295175808   2	I
38.	1995/07/23		1KM		14	I	11	I	A		AL14072395174710   2	1
39.	1995/07/24		1KM		14	ŀ	11	1	A	I	AL14072495173613   2	I
40.	1995/07/28	ļ	1KM		14	1	11		A	I	AL14072895183428   2	
41.	1995/07/29	I	1KM	1	14		11	1	A	١	AL14072995182331   2	I
42.	1995/07/30		1KM		14	1	11		A		AL14073095181246   2	
43.	1995/07/31		1KM	ļ	14		11		A	]	AL14073195180135   2	
44.	1995/08/01		1KM		14		11		A	]	AL14080195175039   2	
45.	1995/08/02		1KM	ł	14	1	11	ļ	A		AL14080295173938   2	
46.	1995/08/06		1KM		14		12	1	A	I	AL14080695183752   2	l
47.	1995/08/07	ļ	1KM		14	1	12	I	A		AL14080795182653   2	
48.	1995/08/08	I	1KM		14		12		A		AL14080895181554   2	
49.	1995/08/09	1	1KM		14		12		A		AL14080995180459   2	

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50. 1995/08/10   1KM   14   11   A   AL14081095175404   2	I
51. 1995/08/11   1KM   14   11   A   AL14081195174300   2	ł
52. 1995/08/16   1KM   14   11   A   AL14081695183018   2	
53. 1995/08/17   1KM   14   11   A   AL14081795181922   2	
54. 1995/08/18   1KM   14   11   A   AL14081895180822   2	
55. 1995/08/19   1KM   14   11   A   AL14081995175743   2	
56. 1995/08/20   1KM   14   11   A   AL14082095174631   2	I
57. 1995/08/21   1KM   14   11   A   AL14082195173534   2	I
58. 1995/08/25   1KM   14   11   A   AL14082595183342   2	I
59. 1995/08/26   1KM   14   12   A   AL14082695182245   2	1
60. 1995/08/27   1KM   14   12   A   AL14082795181147   2	
61. 1995/08/28   1KM   14   11   A   AL14082895180101   2	
62. 1995/08/29   1KM   14   12   A   AL14082995174959   2	ļ
63. 1995/08/30   1KM   14   11   A   AL14083095173903   2	1
64. 1995/09/03   1KM   14   11   A   AL14090395183704   2	I
65. 1995/09/04   1KM   14   11   A   AL14090495182604   2	l
66. 1995/09/05   1KM   14   11   A   AL14090595181506   2	
67. 1995/09/06   1KM   14   11   A   AL14090695180408   2	1
68. 1995/09/07   1KM   14   11   A   AL14090795175309   2	ļ
<b>69</b> . 1995/09/08   1KM   14   11   A   AL14090895174230   2	I
70. 1995/09/13   1KM   14   11   A   AL14091395182924   2	l
71. 1995/09/14   1KM   14   11   A   AL14091495181826   2	ł
72. 1995/09/15   1KM   14   11   A   AL14091595180728   2	
73. 1995/09/16   1KM   14   11   A   AL14091695175633   2	1
74. 1995/09/17   1KM   14   11   A   AL14091795174535   2	ļ
75. 1995/09/22   1KM   14   12   A   AL14092295183249   2	1
76. 1995/09/23   1KM   14   11   A   AL14092395182200   2	1
77. 1995/09/24   1KM   14   11   A   AL14092495181105   2	]
78. 1995/09/25   1KM   14   11   A   AL14092595180012   2	ł
<b>79.</b> 1995/09/26   1KM   14   12   A   AL14092695174851   2	1

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80.	1995/09/27		1KM	{	14	1	12	{	A	۱	AL14092795173755   2	
81.	1995/10/01	ł	1KM	]	14	ł	11	ļ	Α	1	AL14100195183600   2	
82.	1995/10/02		1KM	l	14		11	ļ	A	1	AL14100295182505   2	l
83.	1995/10/03		1KM	ł	14	1	11	ļ	A	1	AL14100395181143   2	[
84.	1995/10/04		1KM		14	١	11	١	A	1	AL14100495180029   2	
85.	1995/10/05	]	1KM	I	14	ļ	11	ł	A	ł	AL14100595174934   2	
86.	1995/10/10		1KM	1	14	I	11	1	A	1	AL14101095183655   2	1
87.	1995/10/11	1	1KM		14		11	ł	A	I	AL14101195182548   2	1
88.	1995/10/12	1	1KM	۱	14	I	11		A	Ι	AL14101295181445   2	I
89.	1995/10/13	ł	1KM	۱	14	.	11		A	l	AL14101395180346   2	I
90.	1995/10/14	ļ	1KM		14	I	12	l	A	I	AL14101495175248   2	]
91.	1995/10/15		1KM	۱	14		12	ł	A	I	AL14101595174148   2	I
92.	1995/10/16	1	1KM	1	14	1	12	١	A	l	AL14101695173050   2	1
93.	1995/10/20	l	1KM		14		11	I	A	Ι	AL14102095182901   2	
94.	1995/10/21	1	1KM	1	14		11	ł	A	ł	AL14102195181803   2	
95.	1995/10/22	1	1KM	1	14		11	[	A	ł	AL14102295180705   2	
96.	1995/10/23	1	1KM		14		11		A	ł	AL14102395175605   2	I
<b>9</b> 7.	1995/10/24		1KM		14	I	11		A	!	AL14102495174506   2	]
98.	1995/10/29	l	1KM	1	14	I	11	I	A		AL14102995183215   2	
99.	1995/10/30	1	1KM	ļ	14	1	11		A	1	AL14103095182120   2	
100.	1995/10/31		1KM	ł	14	I	11		A		AL14103195181014   2	
101.	1995/11/01		1KM	I	14	I	11	]	A		AL14110195175919   2	ł
102.	1995/11/02	I	1KM		14	I	11	1	A		AL14110295174817   2	
103.	1995/11/03	ļ	1KM	ł	14	ļ	11	ļ	A	ł	AL14110395173717   2	
104.	1995/11/07		1KM	۱	14	I	11	l	A	1	AL14110795183531   2	1
105.	1995/11/08	ļ	1KM		14		11		A	1	AL14110895182429   2	
106.	1995/11/09	1	1KM	ł	14	ł	11	1	A	ł	AL14110995181331   2	1
107.	1995/11/10	I	1KM		14		11		A	I	AL14111095180231   2	
108.	1995/11/11		1KM	I	14	l	11		A		AL14111195175131   2	
109.	1995/11/12	1	1KM	1	14		11	1	A	[	AL14111295174035   2	1

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110.	1995/11/16		1KM	۱	14		11	۱	A	١	AL14111695184116   2	
111.	1995/11/17		1KM	١	14	1	11	1	A	I	AL14111795183030   2	
112.	1995/11/18	l	1KM	١	14		11	1	A		AL14111895181920   2	
113.	1995/11/19		1KM	ļ	14	1	11		A	ļ	AL14111995180821   2	
114.	1995/11/20	ł	1KM		12	1	4		D	I	AL12112095103722   2	
115.	1995/11/20		1KM	1	14	1	11	ļ	A	۱	AL14112095175719   2	
116.	1995/11/21		1KM	l	14	ļ	11		A		AL14112195174618   2	
117.	1995/11/22		1KM		14	I	11	1	A	1	AL14112295173519   2	1
118.	1995/11/26		1KM	ļ	14	l	11		A	I	AL14112695183328   2	
119.	1995/11/27	I	1KM	ļ	14	ł	11	۱	A	ļ	AL14112795182239   2	
120.	1995/11/28	ŀ	1KM	I	14	ļ	11		A		AL14112895181139   2	I
121.	1995/11/29	l	1KM		12	1	4	l	D	I	AL12112995104128   2	
122.	1995/11/29		1KM	1	14	1	11		A	١	AL14112995180026   2	
123.	1995/12/01	l	1KM	ł	14	ļ	11	I	A	Ι	AL14120195173828   2	
124.	1995/12/05	I	1KM	1	14		11		A	1	AL14120595183633   2	
125.	1995/12/06	I	1KM		14	ł	11		A		AL14120695182545   2	
126.	1995/12/07		1KM		14	!	11		A	l	AL14120795181434   2	
127.	1995/12/08		1KM		14	ł	11	I	A	I	AL14120895180335   2	
128.	1995/12/09		1KM	]	14		10		A		AL14120995175300   2	
129.	1995/12/10		1KM	ł	14	!	11		A	1	AL14121095174136   2	
130.	1995/12/14		1KM	ł	14	1	12		A		AL14121495183953   2	]
131.	1995/12/16	۱	1KM	1	14		11	1	A	١	AL14121695181745   2	
132.	1995/12/17		1KM	1	14		11	l	A		AL14121795180644   2	
133.	1995/12/18		1KM	۱	14	I	12		A	1	AL14121895175555   2	1
134.	1995/12/19	l	1KM	1	14		12		A		AL14121995174447   2	1
135.	1995/12/24		1KM		14	I	12		A	1	AL14122495183152   2	
136.	1995/12/25		1KM		14	1	12		A		AL14122595182053   2	
137.	1995/12/26	ł	1 KM	1	14	I	12		A	l	AL14122695180949   2	
138.	1995/12/27	1	1KM		14		12	1	A		AL14122795175853   2	
139.	1995/12/28	1	1 KM	1	14	1	12		A	1	AL14122895174749   2	

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•	140.	1996/01/02	l	1KM	14	1	12	2	A		AL14010296183455	1	2	1	1	[
	141.	1996/01/03		1KM	14	I	12	2	A		AL14010396182356	I	2		l	1
	142.	1996/01/04	1	1KM	14	1	11	2	A		AL14010496181303	ł	2			
	143.	1996/01/05	I	1KM	14	1	11		A		AL14010596180200		2	]		1
	144.	1996/01/06	ł	1KM	14	l	11	.	A		AL14010696175107	1	2	I	1	
	145.	1996/01/07		1KM	14	1	11	-	A		AL14010796174006	1	2	I		
	146.	1996/01/11		1KM	14	ļ	11	.	A		AL14011196183802	ł	2	ł		
	147.	1996/01/12		1KM	14		11	.	A		AL14011296182703		2	I	!	
	148.	1996/01/13		1KM	14	1	11		A	j	AL14011396181601	ļ	2	1		
	149.	1996/01/14		1KM	14		11	.	A	İ	AL14011496180511	I	2			
	150.	1996/01/15		1KM	14	1	11	1	A	ĺ	AL14011596175402		2	1		
	151.	1996/01/20		1KM	14		11	.	A		AL14012096184118	!	2	1	1	
	152.	1996/01/21		1KM  ·	14		11		A		AL14012196183007	۱	2			}
	153.	1996/01/22		1KM	14		11	]	A	]	AL14012296181908	ļ	2	ļ		
	154.	1996/01/23		1KM	14		11	.	A		AL14012396180804		2			l
	155.	1996/01/24	1	1KM	14		11	.	A	[	AL14012496175711	1	2			
	156.	1996/01/25		1KM	14		11	1	A	ł	AL14012596174603	ł	2			l
	157.	1996/01/30		1KM	14	I	11	.	A		AL14013096183320	1	2			
	158.	1996/01/31	]	1KM	14	]	11	].	A	ļ	AL14013196182207		2	ļ		
	159.	1996/02/01		1KM	14		11	.	A	1	AL14020196181106	1	2	ļ		I
	160.	1996/02/03		1KM	14	1	11	.	A		AL14020396174912	ł	2	ł		
	161.	1996/02/04		1KM	14	I	11	.	A		AL14020496173818	l	2			1
	162.	1996/02/08		1KM	14		11	] ]	A		AL14020896183611	1	2			
	163.	1996/02/09	ļ	1KM	14	1	11	1	A		AL14020996182519	ļ	2			
	164.	1996/02/10	1	1KM	14		11	2	A		AL14021096181417		2			ļ
	165.	1996/02/11	1	1KM	14	1	11	2	₽		AL14021196180308		2	ł		1
	166.	1996/02/12	}	1KM	14		11	2	A		AL14021296175208	1	2			١
	167.	1996/02/13		1KM	14	1	11	2	A		AL14021396174107		2			
	168.	1996/02/19	ļ	1KM	14	1	11	2	z		AL14021996181710		2	ł	}	
	169.	1996/02/20	1	1KM	14	ļ	11	2	<del>7</del>		AL14022096180619		2	ļ	1	1

170.	1996/02/21	۱	1KM	Į	14	1	11		A		AL14022196175506	I	2	1		ł
171.	1996/02/22		1KM		14		10	1	A	۱	AL14022296174404	l	2	-		
172.	1996/02/26		1KM	1	14		11	l	A	١	AL14022696184206	1	2	1		I
173.	1996/02/27	I	1KM	ļ	14	1	11	I	A	I	AL14022796183112	I	2	1		1
174.	1996/02/28		1KM	1	14	1	11		A	1	AL14022896182006		2	ļ		]
175.	1996/02/29	ł	1KM	ļ	12		2		D	I	AL12022996103903	I	2			1
176.	1996/02/29		1KM	ļ	14		11		A	1	AL14022996180905	I	2			
177.	1996/03/01		1KM		14		11	I	A	ļ	AL14030196175804	ļ	2	1		l
178.	1996/03/02	l	1KM		14		11		A	۱	AL14030296174716		2	I		1
179.	1996/03/06	ļ	1KM	İ	14	ł	11		A		AL14030696184505	1	2			
180.	1996/03/07		1KM	1	14		11	1	A	I	AL14030796183405	1	2			
181.	1996/03/09		1KM		14		11	1	A	I	AL14030996181202	1	2	1		1
182.	1996/03/10		1KM		14		11		A	I	AL14031096180102		2		ļ	
183.	1996/03/11	ļ	1KM	1	14		11		A	I	AL14031196175001	1	2	1	!	1
184.	1996/03/11		1KM		14		11	l	A		AL14031196175001	1	2	1		1
185.	1996/03/12		1KM	I	14	1	11		A		AL14031296173900		2	l	1	1
186.	1996/03/14		1KM		12		3		D		AL12031496103213		2		[	I
187.	1996/03/16		1KM	1	14		11		A	I	AL14031696183714	Į	2	I		
188.	1996/03/17		1KM		14		11		A	Ι	AL14031796182610		2	I	I	1
189.	1996/03/18	I	1KM		14	1	11		A		AL14031896181502	I	2			
190.	1996/03/20	ł	1KM	1	14		12	1	A	ļ	AL14032096175255	1	2	]	I	1
191.	1996/03/21		1KM		14	1	11		A	I	AL14032196174203	1	2		1	
192.	1996/03/25		1KM	1	14		12	I	A	1	AL14032596183953		2			I
193.	1996/03/26	1	1KM	I	14	ļ	12		A	I	AL14032696182852	I	2			ļ
194.	1996/03/27		1KM	!	14		12		A		AL14032796181752		2			
195.	1996/03/28		1KM		14		12	ļ	A	ł	AL14032896180655		2			1
196.	1996/03/30		1KM	ł	14		12		A		AL14033096174447		2			I
197.	1996/04/03		1KM	۱	14	1	12		A		AL14040396184252		2			
198.	1996/04/04		1KM	ļ	14		12		A		AL14040496183149		2			I
199.	1996/04/05		1KM	1	14		12	ļ	A		AL14040596182051		2		[	

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200.	1996/04/06	1KM	14	12	A	AL14040696180949	1	2	1	l	
201.	1996/04/07	1KM	14	12	A	AL14040796175849	1	2			ł
202.	1996/04/08	1KM	14	11	A	AL14040896174744		2	I	I	1
203.	1996/04/12	1KM	14	12	A	AL14041296184546	I	2	I	I	
204.	1996/04/13	1KM	14	11	A	AL14041396183443	I	2	I	1	
205.	1996/04/14	1KM	14	11	A	AL14041496182342		2	I	1	1
206.	1996/04/15	1KM	12	4	D	AL12041596103441		2			
207.	1996/04/15	1KM	14	11	A	AL14041596181239		2	ł	I	ļ
208.	1996/04/16	1KM	14	11	A	AL14041696180143	ļ	2	1		1
209.	1996/04/17	1KM	14	11	A	AL14041796175038		2		]	
210.	1996/04/18	1KM	14	11	A	AL14041896173938		2			
211.	1996/04/22	1KM	14	11	A	AL14042296183738		2	1	ł	1
212.	1996/04/23	1KM	14	11	A	AL14042396182631	ł	2		i	ļ
213.	1996/04/24	1KM	14	11	a	AL14042496181530	1	2		1	l
214.	1996/04/25	1KM	14	11	a	AL14042596180429		2	I	1	
215.	1996/04/26	1KM	14	11	A	AL14042696175327		2	[	1	1
216.	1996/04/27	1KM	14	11	A	AL14042796174226		2	1	ł	
217.	1996/05/01	1KM	14	11	A	AL14050196184026	ł	2	1		
218.	1996/05/03	1KM	14	11	A	AL14050396181824	1	2	1	1	
219.	1996/05/04	1KM	14	11	A	AL14050496180722		2			
220.	1996/05/05	1KM	14	11	A	AL14050596175625		2			1
221.	1996/05/06	1KM	14	11	A	AL14050696174519	ļ	2	I		
222.	1996/05/10	1KM	14	11	A	AL14051096184319		2	I	1	]
223.	1996/05/11	1KM	14	11	A	AL14051196183226		2	1		
224.	1996/05/12	1KM	14	11	A	AL14051296182115		2		1	
225.	1996/05/13	1KM	14	11	A	AL14051396181014		2		1	
226.	1996/05/14	1KM	14	11	A	AL14051496175911		2			
227.	1996/05/15	1KM	14	11	A	AL14051596174809		2	]	]	
228.	1996/05/19	1KM	14	11	A	AL14051996184607		2	1		
229.	1996/05/20	1KM	14	11	A	AL14052096183507	ļ	2			

230.	1996/05/21	1	1KM	14	1	11	ł	A		AL14052196182416		2	ł	ł	l
231.	1996/05/22	ł	1KM	12	1	4		D	ł	AL12052296102740	1	2	-	1	!
232.	1996/05/22		1KM	14	1	11		A	l	AL14052296181312	ļ	2		1	
233.	1996/05/23	I	1KM	14		12	1	A	I	AL14052396180159	]	2		ł	ł
234.	1996/05/24	1	1KM	14	I	12	1	A	I	AL14052496175056	1	2			
235.	1996/05/28	ļ	1KM	14	1	11		A	ļ	AL14052896184900		2			1
236.	1996/05/29		1KM	14		12		A	ļ	AL14052996183755		2			1
237.	1996/05/30		1KM	14	ļ	11		A		AL14053096182701		2			1
238.	1996/05/31	ł	1KM	14	1	11	۱	A	I	AL14053196181608	l	2			I
239.	1996/06/01	ł	1KM	14	I	12	ļ	A	1	AL14060196180450	I	2			1
240.	1996/06/02		1KM	14	[	12	I	A	1	AL14060296175348		2			1
241.	1996/06/03		1KM	14	ļ	12	ļ	A	1	AL14060396174251		2	ļ	1	l
242.	1996/06/07		1KM	14	1	11		A		AL14060796184043	١	2	1	1	
243.	1996/06/08	1	1KM	14	ļ	11	1	A		AL14060896182953	1	2		ł	1
244.	1996/06/09		1KM	14		11		A	[	AL14060996181842	I	2			
245.	1996/06/10	1	1KM	14		11		A		AL14061096180740	1	2	ļ	1	
246.	1996/06/11	۱	1KM	14	I	11		A	1	AL14061196175637		2	l		
247.	1996/06/12	I	1KM	14		11	l	A		AL14061296174533	1	2			1
248.	1996/06/16		1KM	14	1	11	I	A	I	AL14061696184330	I	2	1		ļ
249.	1996/06/17		1KM	14	ł	11		A	1	AL14061796183229	1	2	]	!	
250.	1996/06/18		1KM	14	1	11	I	A		AL14061896182123		2			
251.	1996/06/19		1KM	14	1	11		A	ł	AL14061996181023		2		1	
252.	1996/06/20	ļ	1KM	14	I	11		A		AL14062096175919		2		I	l
253.	1996/06/21	1	1KM	14	1	11	1	A		AL14062196174818	1	2	1		1
254.	1996/06/25	1	1KM	14	I	11	l	A	1	AL14062596184614		2	ł	]	[
255.	1996/06/26		1KM	14	I	11		A		AL14062696183512		2	[		]
256.	1996/06/27	]	1KM	14		11		A		AL14062796182412	ļ	2		1	]
257.	1996/06/28		1KM	14		11	l	A		AL14062896181308	ł	2	1		]
258.	1996/06/29		1KM	14		11	1	A		AL14062996180205	1	2			
259.	1996/06/30		1KM	14		11		A		AL14063096175103		2	ļ		

260.	1996/07/04	1	1KM	l	14		11		Α		AL14070496184903   2	ļ
261.	1996/07/05	1	1KM	I	14	I	12	l	A	۱	AL14070596183758   2	۱
262.	1996/07/06		1KM	I	14	Ι	11		A	1	AL14070696182711   2	I
263.	1996/07/07	1	1KM	ļ	14	1	11	I	A	I	AL14070796181602   2	
264.	1996/07/08	l	1KM		14	I	12	1	A		AL14070896180450   2	
265.	1996/07/09		1KM	l	14	l	12		A		AL14070996175350   2	
266.	1996/07/14	1	1KM	1	14	1	11	1	A	1	AL14071496184039   2	
267.	1996/07/15	1	1KM	I	14	I	11		A	!	AL14071596182939   2	
268.	1996/07/16		1KM	I	14	l	11	ļ	A	1	AL14071696181834   2	
269.	1996/07/17		1KM	I	14	ł	11	1	A	۱	AL14071796180735   2	۱
270.	1996/07/18	۱	1KM	ļ	14	l	11	١	A	l	AL14071896175641   2	
271.	1996/07/19	1	1KM	ł	14	l	11	1	A	I	AL14071996174525   2	ļ
272.	1996/07/23	I	1KM	1	14	1	11	l	A	1	AL14072396184321   2	1
273.	1996/07/24		1KM		14	l	11	I	A		AL14072496183220   2	
274.	1996/07/25		1KM	1	14	[	11	!	A		AL14072596182117   2	1
275.	1996/07/26	!	1KM	1	14	I	11	1	A	İ	AL14072696181013   2	
276.	1996/07/27	ł	1KM	I	14	l	11	I	A	1	AL14072796175910   2	
277.	1996/07/28		1KM	l	14		11		A		AL14072896174812   2	
278.	1996/08/01	1	1KM		14	I	11	ł	A	I	AL14080196184603   2	

#### **Actions**

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#### **Appendix 4.2 Root Mean Square Error**

$$RMSE = \sqrt{(x_r - x_i)^2} + (y_r - y_i)^2$$

Where:

 $\boldsymbol{x}_i$  and  $\boldsymbol{y}_i$  are the input source co-ordinates

 $x_r$  and  $y_r$  are the re-transformed co-ordinates

RMS error is expressed as a distance in the source co-ordinate system, i.e. pixel widths.



**Appendix 4.3 Calibration Coefficients for ATSR-2** 

ľ			Coefficients	NOT TAXOR		
	Date + time	Time UTC	VIS-1	VIS-2	VIS-3	NIR
		(from 01-01-95)	(0.56um)	(0.66um)	(0.87um)	1.6 um
	9507011039	182.44398	0.00004752	0.00005051	0.00004298	0.00006023
	9507020646	183.28233	0.00004751	0.00005046	0.00004298	0.00006009
	9507030755	184.33025	0.00004749	0.00005051	0.00004307	0.00006001
	9507040904	185.37817	0.00004753	0.00005067	0.00004316	0.00005996
	9507050832	186.35622	0.00004762	0.00005100	0.00004339	0.00006018
	9507060801	187.33429	0.00004750	0.00005125	0.00004346	0.00006033
	9507070910	188.38220	0.00004748	0.00005152	0.00004354	0.00006055
	9507080838	189.36028	0.00004748	0.00005173	0.00004355	0.00006070
	9507090807	190.33835	0.00004749	0.00005188	0.00004350	0.00006074
	9507100735	191.31642	0.00004750	0.00005195	0.00004341	0.00006068
	9507110844	192.36435	0.00004749	0.00005198	0.00004331	0.00006059
	9507120813	193.34241	0.00004771	0.00005210	0.00004335	0.00006065
	9507130741	194.32047	0.00004764	0.00005197	0.00004327	0.00006055
	9507140850	195.36841	0.00004765	0.00005179	0.00004320	0.00006042
	9507150818	196.34648	0.00004764	0.00005161	0.00004321	0.00006043
	9507160747	197.32455	0.00004766	0.00005140	0.00004321	0.00006041
-	9507170856	198.37251	0.00004764	0.00005120	0.00004328	0.00006054
	9507180824	199.35059	0.00004761	0.00005104	0.00004336	0.00006068
	9507190753	200.32866	0.00004763	0.00005095	0.00004343	0.00006078
	9507200902	201.37660	0.00004759	0.00005091	0.00004355	0.00006094
	9507210830	202.35468	0.00004761	0.00005091	0.00004359	0.00006097
	9507220759	203.33275	0.00004761	0.00005099	0.00004364	0.00006102
	9507230908	204.38071	0.00004760	0.00005108	0.00004363	0.00006093
	9507240836	205.35881	0.00004758	0.00005123	0.00004360	0.00006086
	9507250805	206.33688	0.00004760	0.00005140	0.00004356	0.00006077
	9507260914	207.38483	0.00004758	0.00005157	0.00004348	0.00006067
-	9507270842	208.36292	0.00004758	0.00005171	0.00004338	0.00006058
Ì	9507290739	210.31909	0.00004757	0.00005191	0.00004324	0.00006054
	9507300848	211.36707	0.00004751	0.00005196	0.00004320	0.00006062
	9507310816	212.34514	0.00004755	0.00005196	0.00004317	0.00006068
	9508010745	213.32324	0.00004750	0.00005193	0.00004320	0.00006081
	9508020854	214.37119	0.00004750	0.00005192	0.00004309	0.00006045
	9508030822	215.34927	0.00004751	0.00005184	0.00004313	0.00006052

9508040751	216.32738	0.00004751	0.00005172	0.00004319	0.00006059
9508050900	217.37535	0.00004750	0.00005156	0.00004326	0.00006062
9508060828	218.35345	0.00004746	0.00005137	0.00004330	0.00006059
9508070757	219.33154	0.00004746	0.00005123	0.00004334	0.00006053
9508080906	220.37950	0.00004744	0.00005111	0.00004336	0.00006045
9508090834	221.35760	0.00004748	0.00005100	0.00004336	0.00006037
9508101124	222.47545	0.00004748	0.00004846	0.00004181	0.00005849
9508101305	222,54530	0.00004748	0.00004853	0.00004194	0.00005865
9508101445	222.61517	0.00004748	0.00004853	0.00004200	0.00005873
9508101626	222.68503	0.00004748	0.00004852	0.00004203	0.00005877
9508101807	222.75491	0.00004748	0.00004851	0.00004207	0.00005881
9508101947	222.82477	0.00004748	0.00004848	0.00004207	0.00005883
9508102128	222.89462	0.00004748	0.00004847	0.00004209	0.00005886
9508110912	223.38367	0.00004748	0.00004847	0.00004210	0.00005887
9508120840	224.36180	0.00004748	0.00004846	0.00004209	0.00005886
9508130809	225.33987	0.00004748	0.00004845	0.00004209	0.00005885
9508140737	226.31799	0.00004709	0.00004844	0.00004208	0.00005884
9508140918	226.38786	0.00004709	0.00004854	0.00004212	0.00005880
9508141059	226.45772	0.00004709	0.00004888	0.00004214	0.00005874
9508141239	226.52759	0.00004748	0.00004922	0.00004218	0.00005878
9508141420	226.59744	0.00004850	0.00004947	0.00004223	0.00005886
9508141600	226.66731	0.00004705	0.00004957	0.00004225	0.00005891
9508141741	226.73718	0.00004715	0.00004960	0.00004228	0.00005896
9508141922	226.80704	0.00004712	0.00004962	0.00004229	0.00005899
9508142102	226.87691	0.00004709	0.00004966	0.00004231	0.00005904
9508150706	227.29611	0.00004710	0.00004986	0.00004246	0.00005928
9508150846	227.36597	0.00004712	0.00004991	0.00004250	0.00005935
9508151027	227.43582	0.00004714	0.00004994	0.00004253	0.00005940
9508151208	227.50569	0.00004715	0.00004998	0.00004255	0.00005943
9508151348	227.57553	0.00004714	0.00005001	0.00004257	0.00005946
9508151529	227.64542	0.00004715	0.00005004	0.00004258	0.00005949
9508151709	227.71527	0.00004711	0.00005009	0.00004260	0.00005953
9508151850	227.78514	0.00004708	0.00005011	0.00004262	0.00005957
9508152031	227.85501	0.00004715	0.00005015	0.00004265	0.00005960
9508160634	228.27419	0.00004710	0.00005038	0.00004279	0.00005981
9508170743	229.32219	0.00004710	0.00005095	0.00004312	0.00006027
9508180712	230.30028	0.00004704	0.00005150	0.00004341	0.00006053
9508190640	231.27840	0.00004708	0.00005203	0.00004362	0.00006062
9508200749	232.32635	0.00004700	0.00005253	0.00004376	0.00006054
9508210859	233.37433	0.00004706	0.00005299	0.00004381	0.00006024
9508220827	234.35245	0.00004706	0.00005329	0.00004373	0.00005984
9508230755	235.33055	0.00004704	0.00005346	0.00004354	0.00005934
9508240905	236.37854	0.00004697	0.00005352	0.00004326	0.00005882
9508250833	237.35666	0.00004697	0.00005344	0.00004296	0.00005842
9508260802	238.33478	0.00004699	0.00005323	0.00004264	0.00005813
9508270911	239.38274	0.00004695	0.00005290	0.00004232	0.00005801
9508280839	240.36087	0.00004688	0.00005250	0.00004207	0.00005804
9508290808	241.33897	0.00004691	0.00005207	0.00004189	0.00005823
9508300917	242.38695	0.00004687	0.00005152	0.00004175	0.00005858
9508310845	243.36507	0.00004686	0.00005105	0.00004173	0.00005895
9509010814	244.34319	0.00004683	0.00005057	0.00004178	0.00005936
9509020742	245.32132	0.00004675	0.00005007	0.00004188	0.00005972
9509030851	246.36929	0.00004677	0.00004969	0.00004207	0.00006002
9509040820	247.34741	0.00004673	0.00004938	0.00004228	0.00006020
9509050748	248.32553	0.00004671	0.00004915	0.00004250	0.00006023
9509060857	249.37352	0.00004666	0.00004902	0.00004275	0.00006013
9509070826	250.35162	0.00004663	0.00004897	0.00004295	0.00005991
9509080754	251.32974	0.00004667	0.00004908	0.00004313	0.00005962
9509090903	252.37775	0.00004666	0.00004925	0.00004325	0.00005924
9509100832	253.35587	0.00004661	0.00004946	0.00004329	0.00005887
9509110800	254.33400	0.00004662	0.00004977	0.00004326	0.00005855
9509120910	255.38199	0.00004657	0.00005010	0.00004317	0.00005829

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9509130838	256.36011	0.00004659	0.00005048	0.00004303	0.00005814
9509140807	257.33826	0.00004650	0.00005084	0.00004283	0.00005809
9509150916	258.38623	0.00004650	0.00005123	0.00004262	0.00005817
9509160844	259.36438	0.00004648	0.00005156	0.00004240	0.00005830
9509170813	260.34247	0.00004645	0.00005185	0.00004219	0.00005852
9509180741	261.32062	0.00004646	0.00005211	0.00004202	0.00005877
9509190850	262 36859	0 00004641	0.00005230	0 00004185	0.00005905
9509200819	263 34674	0.00004642	0.00005243	0.00004177	0.00005929
9509210747	264 32486	0.00004639	0.00005243	0.00004177	0.00005944
9509210747	265 37286	0.00004638	0.00005245	0.00004109	0.00005957
9509220050	266 25009	0.00004641	0.00005241	0.00004170	0.00005957
9509230625	200.35090	0.00004041	0.00005231	0.00004175	0.00005951
9509241430	207.00055	0.00004030	0.00005208	0.00004100	0.00005952
9509250903	200.37711	0.00004033	0.00005166	0.00004196	0.00005942
9509260831	209.35522	0.0004630	0.00005157	0.00004209	0.00005923
9509270800	270.33334	0.00004623	0.00005123	0.00004222	0.00005899
9509280909	271.38135	0.00004627	0.00005093	0.00004240	0.00005879
9509301307	273.54718	0.00004613	0.00005023	0.00004259	0.00005837
9510010915	274.38559	0.00004614	0.00004996	0.00004264	0.00005828
9510030812	276.34183	0.00004614	0.00004946	0.00004265	0.00005823
9510050849	278.36792	0.00004615	0.00004921	0.00004253	0.00005840
9510060818	279.34607	0.00004608	0.00004912	0.00004241	0.00005853
9510070746	280.32419	0.00004613	0.00004914	0.00004230	0.00005869
9510080855	281.37219	0.00004608	0.00004918	0.00004215	0.00005885
9510090643	282.28043	0.00004599	0.00004922	0.00004200	0.00005895
9510100752	283.32843	0.00004604	0.00004940	0.00004189	0.00005907
9510110902	284.37643	0.00004598	0.00004956	0.00004177	0.00005911
9510120830	285,35455	0.00004590	0.00004973	0.00004169	0.00005910
9510130759	286 33267	0 00004594	0.00004996	0.00004166	0.00005905
9510140908	287 38065	0.00004592	0.00005020	0.00004164	0.00005896
9510150836	288 35876	0.00004587	0.00005039	0.00004164	0.00005882
9510160805	289 33688	0.00004501	0.00005065	0.00004168	0.00005867
9510170014	200.38486	0.00004591	0.00005081	0.00004174	0.00005851
9510170914	290.30400	0.00004590	0.00005001	0.00004174	0.00005831
9510190011	292.34109	0.00004502	0.00005107	0.00004100	0.00005845
9510200920	293.30907	0.00004570	0.00005113	0.00004199	0.00005615
9510210646	294.30719	0.00004573	0.00005118	0.00004206	0.00005813
9510230745	296.32343	0.00004571	0.00005110	0.00004215	0.00005820
9510240854	297.3/140	0.00004566	0.00005100	0.00004217	0.00005828
9510260751	299.32/64	0.00004559	0.00005070	0.00004211	0.00005849
9510270900	300.37561	0.00004558	0.00005052	0.00004205	0.00005859
9510280829	301.35373	0.00004557	0.00005029	0.00004196	0.00005866
9510290617	302.26196	0.00004554	0.00005010	0.00004188	0.00005871
9510300726	303.30994	0.00004549	0.00004987	0.00004178	0.00005875
9510310654	304.28802	0.00004551	0.00004970	0.00004169	0.00005874
9511010623	305.26614	0.00004542	0.00004955	0.00004161	0.00005867
9511020732	306.31412	0.00004531	0.00004932	0.00004150	0.00005858
9511030700	307.29224	0.00004533	0.00004922	0.00004145	0.00005848
9511040629	308.27032	0.00004528	0.00004912	0.00004140	0.00005833
9511050738	309.31830	0.00004527	0.00004905	0.00004137	0.00005820
9511060706	310.29639	0.00004526	0.00004904	0.00004136	0.00005809
9511070635	311.27451	0.00004525	0.00004904	0.00004137	0.00005799
9511081607	312.67178	0.00004523	0.00004910	0.00004144	0.00005794
9511100641	314.27866	0.00004515	0.00004921	0.00004150	0.00005789
9511120718	316.30472	0.00004514	0.00004943	0.00004162	0.00005800
9511130647	317.28281	0.00004514	0.00004956	0.00004167	0.00005807
9511140615	318 26086	0.00004528	0.00004982	0.00004192	0.00005846
9511150724	319 30884	0.00004510	0.00004982	0.00004175	0.00005827
9511160652	320 28602	0.00004506	0.00004002	0.00004175	0.00005824
9511170621	321 26501	0.00004504	0.00005002	0.00004175	0.00005840
9511180720	327 31 200	0.00004304	0.00005005	0.00004175	0.00005040
9511100750	322.01233	0.00004497	0.00000000	0.00004171	0.00003045
9511200627	324 26020	0.00004505	0.00000010	0.0004100	0.00005040
051120002/	224.20920	0.00004500	0.00005017	0.00004102	0.00005033
3311210/30	323.31/14	0.00004490	0.00003010	0.00004134	0.00000003/

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9511220705	326.29523	0.00004493	0.00005014	0.00004146	0.00005830
9511230633	327.27332	0.00004494	0.00005011	0.00004143	0.00005823
9511241926	328,81033	0.00004502	0.00005004	0.00004134	0.00005809
9511250711	329,29935	0.00004497	0.00004996	0.00004130	0.00005803
9511260639	330,27744	0.00004498	0.00004986	0.00004125	0.00005795
9511270748	331.32538	0.00004494	0.00004971	0.00004119	0.00005787
9511270748	331,32538	0.00004494	0.00004971	0.00004119	0.00005787
9511280857	332 37332	0.00004494	0.00004957	0.00004117	0.00005783
9511290826	333 35141	0 00004483	0.00004938	0.00004112	0.00005780
9511300754	334 32950	0.00004491	0.00004930	0.00004116	0.00005782
9512011726	335,72675	0.00004485	0.00004912	0.00004120	0.00005789
9512030800	337,33356	0.00004483	0.00004896	0.00004127	0.00005800
9512050837	339,35959	0.00004485	0.00004886	0.00004138	0.00005815
9512060806	340.33765	0.00004485	0.00004885	0.00004143	0.00005823
9512070915	341.38559	0.00004484	0.00004884	0.00004148	0.00005828
9512080843	342.36365	0.00004482	0.00004887	0.00004152	0.00005833
9512090812	343.34174	0.00004477	0.00004887	0.00004154	0.00005833
9512100921	344,38965	0.00004477	0.00004895	0.00004155	0.00005832
9512110849	345.36771	0.00004469	0.00004900	0.00004153	0.00005828
9512120817	346,34576	0.00004481	0.00004915	0.00004153	0.00005826
9512132251	347.95258	0.00004477	0.00004931	0.00004148	0.00005815
9512140855	348.37177	0.00004479	0.00004938	0.00004148	0.00005817
9512150823	349.34982	0.00004481	0.00004949	0.00004144	0.00005810
9512170901	351.37579	0.00004490	0.00004978	0.00004140	0.00005810
9512180829	352,35382	0.00004493	0.00004990	0.00004138	0.00005811
9512191119	353,47159	0.00004492	0.00005002	0.00004135	0.00005814
9512210835	355,35785	0.00004508	0.00005028	0.00004142	0.00005837
9607020503	549,21045	0.00004912	0.00005394	0.00004571	0.00006515
9607030110	550,04883	0.00004912	0.00005412	0.00004587	0.00006536
9607050147	552.07477	0.00004910	0.00005454	0.00004612	0.00006572
9607060617	553.26245	0.00004907	0.00005477	0.00004626	0.00006589
9607070907	554.38019	0.00004911	0.00005501	0.00004640	0.00006606
9607080835	555.35828	0.00004909	0.00005521	0.00004645	0.00006614
9607090804	556.33636	0.00004910	0.00005542	0.00004660	0.00006627
9607101415	557.59387	0.00004911	0.00005567	0.00004671	0.00006633
9607111343	558.57190	0.00004908	0.00005585	0.00004674	0.00006633
9607120308	559.13080	0.00004907	0.00005595	0.00004677	0.00006633
9607130738	560.31848	0.00004919	0.00005619	0.00004686	0.00006630
9607140205	561.08698	0.00004923	0.00005634	0.00004688	0.00006625
9607160744	563.32257	0.00004901	0.00005664	0.00004701	0.00006619
9607170853	564.37048	0.00004915	0.00005682	0.00004697	0.00006604
9607180641	565.27875	0.00004911	0.00005693	0.00004697	0.00006594
9607190750	566.32666	0.00004907	0.00005704	0.00004696	0.00006581
9607200036	567.02527	0.00004907	0.00005714	0.00004695	0.00006572
9607210145	568.07318	0.00004905	0.00005722	0.00004690	0.00006555
9607220113	569.05127	0.00004902	0.00005732	0.00004687	0.00006541
9607230222	570.09924	0.00004908	0.00005745	0.00004683	0.00006525
9607240833	571.35681	0.00004791	0.00005640	0.00004589	0.00006384
9607250802	572.33484	0.00004797	0.00005648	0.00004581	0.00006368
9607260228	573.10333	0.00004793	0.00005650	0.00004577	0.00006354
9607270839	574.36090	0.00004796	0.00005653	0.00004566	0.00006332
9607280306	575.12939	0.00004789	0.00005651	0.00004559	0.00006318
9607290736	576.31708	0.00004793	0.00005654	0.00004548	0.00006299
9607300845	577.36505	0.00004795	0.00005653	0.00004538	0.00006284
9607310814	578.34308	0.00004785	0.00005647	0.00004524	0.00006268
9608010421	579.18146	0.00004791	0.00005647	0.00004519	0.00006259
9608020711	580.29932	0.00004778	0.00005633	0.00004504	0.00006243
9608030458	581.20752	0.00004775	0.00005626	0.00004492	0.00006233
9608050716	583.30347	0.00004770	0.00005604	0.00004466	0.00006210
9608060645	584.28156	0.00004771	0.00005597	0.00004456	0.00006204
9608070613	585.25964	0.00004769	0.00005583	0.00004445	0.00006201
9608080722	586.30762	0.00004771	0.00005572	0.00004435	0.00006198

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587.35553	0.00004765	0.00005554	0.00004424	0.00006198
588.33368	0.00004773	0.00005546	0.00004414	0.00006201
589.38165	0.00004771	0.00005530	0.00004409	0.00006205
590.35974	0.00004763	0.00005508	0.00004397	0.00006207
592.38580	0.00004761	0.00005474	0.00004382	0.00006219
593.36389	0.00004761	0.00005458	0.00004377	0.00006229
594.34204	0.00004754	0.00005437	0.00004372	0.00006239
595.32013	0.00004762	0.00005425	0.00004367	0.00006249
596.36810	0.00004751	0.00005398	0.00004361	0.00006260
598.32434	0.00004754	0.00005365	0.00004360	0.00006284
599.37225	0.00004742	0.00005338	0.00004353	0.00006294
600.35040	0.00004749	0.00005327	0.00004359	0.00006310
601.67786	0.00004743	0.00005301	0.00004358	0.00006325
602.37653	0.00004735	0.00005284	0.00004354	0.00006332
603.35461	0.00004739	0.00005271	0.00004362	0.00006346
604.33276	0.00004732	0.00005251	0.00004364	0.00006358
605.38074	0.00004731	0.00005234	0.00004368	0.00006368
606.35883	0.00004734	0.00005222	0.00004372	0.00006377
609.36310	0.00004727	0.00005180	0.00004389	0.00006402
	587.35553 588.33368 589.38165 590.35974 592.38580 593.36389 594.34204 595.32013 596.36810 598.32434 599.37225 600.35040 601.67786 602.37653 603.35461 604.33276 605.38074 606.35883 609.36310	587.35553         0.00004765           588.33368         0.00004773           589.38165         0.00004771           590.35974         0.00004763           592.38580         0.00004761           593.36389         0.00004761           593.36389         0.00004761           594.34204         0.00004761           595.32013         0.00004762           596.36810         0.00004754           599.37225         0.00004754           599.37225         0.00004742           600.35040         0.00004743           602.37653         0.00004735           603.35461         0.00004732           604.33276         0.00004731           606.35883         0.00004734           609.36310         0.00004727	587.35553         0.00004765         0.0000554           588.33368         0.00004773         0.00005546           589.38165         0.00004771         0.00005530           590.35974         0.00004763         0.00005508           592.38580         0.00004761         0.00005474           593.36389         0.00004761         0.00005474           593.36389         0.00004761         0.00005478           594.34204         0.00004762         0.00005437           595.32013         0.00004762         0.00005425           596.36810         0.00004754         0.00005398           598.32434         0.00004754         0.00005308           599.37225         0.00004742         0.00005327           601.67786         0.00004735         0.00005301           602.37653         0.00004732         0.00005271           604.33276         0.00004732         0.00005271           605.38074         0.00004734         0.00005234           606.35883         0.00004734         0.00005222           609.36310         0.00004727         0.00005180	587.35553         0.00004765         0.00005554         0.00004424           588.33368         0.00004773         0.00005546         0.00004414           589.38165         0.00004771         0.00005530         0.00004409           590.35974         0.00004763         0.00005508         0.00004397           592.38580         0.00004761         0.00005474         0.00004382           593.36389         0.00004761         0.00005478         0.00004377           594.34204         0.00004762         0.00005437         0.00004372           595.32013         0.00004762         0.00005425         0.00004367           596.36810         0.00004754         0.00005398         0.00004361           598.32434         0.00004754         0.00005365         0.00004360           599.37225         0.00004742         0.00005327         0.00004353           600.35040         0.00004735         0.00005327         0.00004354           602.37653         0.00004732         0.00005271         0.00004362           604.33276         0.00004731         0.00005234         0.00004364           605.38074         0.00004734         0.00005222         0.00004368           606.35883         0.00004727         0.00005222

### Appendix 4.4

## 5S-S5 Atmospheric Correction Procedure (Tanré *et al.* 1990)

$$\rho_{i} = 100Y_{i} / (100 + Y_{i}S_{i}),$$
where
$$Y_{i} = A_{i}D_{s}^{2}L_{i} + B_{i},$$

$$A_{i} = \frac{100\pi}{E_{Oi}\cos\theta_{s}\tau_{g}\tau_{s}\tau_{v},}$$

$$B_{i} = \frac{-100\rho_{atm}}{\tau_{s}\tau_{v}}$$

Where:

And  $\rho$  is surface reflectance (%),

S is the atmospheric spherical albedo,

 $\tau_g$  is the gas transmittance,

 $\tau_s$  is the scattering transmittance in the solar direction,

 $\tau_v$  is the scattering transmittance in the sensor direction,

patm is atmospheric reflectance,

d<sub>s</sub> the solar distance in astronomical units, and,

 $\theta_s$  the solar zenith angle in degrees.

## Appendix 5.1

Where data loss occurred: a mean value was derived (from-the remaining days of the calendar month) and inserted into the absent daily totals. E.g. if no data exists for the last 5 days of month x; the average for the first 25 days of that month would be used for days 26 - 30 inclusive.

Hemi-	No. of tie	RMSE	Hemi-	No. of tie	RMSE	Hemi-	No. of tie	RMSE
Photo No.	points	(Pixels)	Photo No.	points	(Pixels)	Photo No.	points	(Pixels)
	Point 1	Point 1		Point 2	Point 2		Point 3	Point 3
Date1	Datum	Datum	Date1	Datum	Datum	Date1	Datum	Datum
Date2	16	7.2	Date2	12	4.1	Date2	8	23
Date3	21	6.2	Date3	11	7.1	Date3	13	17
Date4	19	5.9	Date4	21	7.1	Date4	16	6.1
Date5	17	3.1	Date5	22	4.9	Date5	11	4.9
Date6	12	10.2	Date6	25	17	Date6	8	12.4
Date7	11	5.7	Date7	16	2.8	Date7	10	7.9
Date8	14	7.1	Date8	19	2.2	Date8	12	10
Date9			Date9			Date9		
Date10	15	4.8	Date10			Date10		
Date11	16	6	Date11			Date11		
Date12	13	7.1	Date12			Date12		
Hemi-	No. of tie	RMSE	Hemi-	No. of tie	RMSE	Hemi-	No. of tie	RMSE
Photo No.	points	(Pixels)	Photo No.	points	(Pixels)	Photo No.	points	(Pixels)
	Point 4	Point 4		Point 5	Point 5		Point 7	Point 7
Date1	Datum	Datum	Date1	Datum	Datum	Date1	Datum	Datum
Date2	12	4.1	Date2	12	3.2	Date2	12	6.2
Date3	9	6.2	Date3	18	2.1	Date3	17	2.7
Date4	25	7	Date4	14	3.3	Date4	11	8.5
Date5	21	9.5	Date5	16	6.4	Date5	21	8.2
Date6	19	6.1	Date6	12	1.2	Date6	15	7.6
Date7	14	3.6	Date7	5	0.6	Date7	12	2
Date8	13	3.7	Date8	9	4.4	Date8	19	2.7
Date9			Date9	10	5	Date9	8	2.9
Date10	9	4.7	Date10	11	6.3	Date10	11	8.4
Date11	13	4.3	Date11	13	8.3	Date11	14	5.5
Date12			Date12		····	Date12		

## Appendix 5.2

Hemi-	No. of tie	RMSE		
Photo No.	points	(Pixels)		
	Point 7	Point 7		
Date1	Datum	Datum		
Date2	20	3.6		
Date3	18	2.1		
Date4	11	3.8		
Date5	13	3.7		
Date6	18	2.7		
Date7	13	6		
Date8	12	5.1		
Date9	10	3.1		
Date10	18	1.7		
Date11	10	6.6		
Date12				

#### **Appendix 5.3 Pearson's correlation**

$$r = \frac{n(\sum XY) - (\sum X)(\sum Y)}{\sqrt{[n\sum X^2 - (\sum X)^2][n\sum Y^2 - (\sum Y)^2]}}$$

where r is the correlation, and

X and Y the Quantitative data in the two

Coefficient of determination (r-2) the sum of the squared differences between the y-value estimated for each point and its actual value (residual sum of squares); sum of the squared differences between the actual y-values and the average of the y-values, (total sum of squares - regression sum of squares + residual sum of squares). The smaller the residual sum of squares compared to the total sum of squares the larger the coefficient of determination (r-2).

Figure 2.1

after Walsh (1996)



## Locations of the Monitored Forest Sites

		Monitored Sites	① Chapare	② Lomerio	③ Las Trancas
	Schemes	Life Zone System, Holdridge et al. (1971)	Rain Forest	Moist Forest	Savanna
Andes Humid Sub-Humid Low-lands Brasilian Shield	Classification	Vegetac ♥ o da Brasil Veloso et al. (1991)	Dense Rain Forest, Seasonally Inundated, Uniform Canopy	Seasonal Semi- Deciduous Forest, Lowland, Canopy with Emergents	Savanna Aborizada



Figure 2.4 General Circulation of Neotropical Air Masses after Vaun-Williams (1982)



Figure 2.7

# Reflection, Absorption & Transmittance of Green Vegetation After Lloyd (1989a); Knipling (1970)





Figure 2.8 Generalised leaf physiology



Figure 2.9

Comparison of the action spectrum for photosynthesis with the absorption spectra of leaves and their pigments, Jones (1992)













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Figure 2.16 Seasonal Development of an Idealised Vegetation Index (in Southern hemisphere), after Tucker (1979)



2.17 NDVI Temporal Curves in Selected African Tropical Forests (after Justice et al., 1986)







Figure 2.19 Factors Affecting the Remote Sensing of Phenology

## Figure 3.1 Locations of the Three Monitored Vegetation Communities









Figure 3.4 Ecological Inventory at Lomerio



Figure 3.5 BOLFOR95 Hemispherical Photo locations & Ceptometer Transects at Lomerio



Figure 3.6 The Spectral Response Curve (Before Filtering) of the TSL250 Silicon Photodiode Used in this Study





Figure 3.8 Spectral Response Curve of TSL260 (Unaffected by filtering)



Figure 3.9 Output Voltage Response of the TSL250



Figure 3.10 Temperature and Supply Voltage Dependency





Figure 4.1 Along-Track and Across-Track Variation in IFOV as a Function of View Zenith, after Goward *et al.*, (1991)



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Variation in Reflectance Precision with of Solar Zenith, after Goward et al., (1991)


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Figure 4.3 Variation in View Zenith as a Function of Latitude, after Goward et al., (1991)







## Figure 4.5 Temporal Distribution of AVHRR Images by Ground Verification Site



## Temporal Distribution of AVHRR Images by View Angle (Lomerio)







Figure 4.7

## Temporal Distribution of AVHRR Images by View Angle (Chapare)



Figure 4.8



Figure 4.9 IMAGE PROCESSING METHODOLOGY



1995 - 1996





Mean Monthly Relative Humidity and Potential Evaporation,

Figure 5.3

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1995 - 1996





Figure 5.4



.

## **Precipitation minus Potential Evaporation, Las Trancas**







## **Daily Mean Dry Bulb Temperatures & Precipiation, Chapare**





NOVEMBER\*

DECEMBER\*

SEPTEMBER\*

OCTOBER

Mean Monthly Relative Humidity and Potential Evaporation,

JANUARY

1995 - 1996

FEBRUARY\*

MARCH\*

100

90.

80

70

60

50

JUNE\*

MAY

\* Incomplete Data for these Months

APRIL

Data Extrapolated

.

RH (%)

Figure 5.8



## **Accumulated Daily Precipitation Chapare**





## **Precipitation minus Potential Evaporation, Chapare**





### Litterfall (dry weights -converted to drop dates) Seasonal semi-deciduous TF





.

# Litterfall (Dry Weights)







## Correlations between mean monthly Temperature (Las Trancas)





#### Correlations between mean monthly Temperature (Las Trancas) and total monthly leaf fall (Seasonal semi-deciduous TF)

Monthly Temperature vs. Total Litterfall & Leaf fall



Lomerio (Seasonally deciduous tropical forest)





#### Correlations between monthly Precipitation (Las Trancas) and total monthly litterfall (Seasonal demi-deciduous TF)





#### Correlations between monthly Precipitation (Las Trancas) and monthly leaf fall (Seasonal semi-deciduous TF)

**.**..

Monthly Precipitation vs. Total Litterfall & Leaf fall



Lomerio (Seasonally deciduous tropical forest)





#### Correlations between mean monthly Relative Humidity (Las Trancas) and total monthly litterfall (Seasonal semi-deciduous TF)





Correlations between mean monthly Relative Humidity (Las Trancas) and monthly leaf fall (Seasonal semi-deciduous TF) Relative Humidity vs. Total Litterfall & Leaf fall



Lomerio (Seasonally deciduous tropical forest)

#### Correlations between mean monthly Potential Evaporation (Las Trancas) and total monthly titterfall (Seasonal semi-deciduous TF)









Potential Evaporation vs. Total Litterfall & Leaf fall

## Lomerio (Seasonally deciduous tropical forest)

## Monthly Precipiation - Potential Evaporation

vs. Total Litterfall & Leaf fall Lag = +1 Month



Lomerio (Seasonally deciduous tropical forest)

### Direct phenological observations of the ground-stratum Seasonal semi-deciduous TF



### Direct phenological observations of the sub-canopy stratum Seasonal semi-deciduous TF


### Figure 5.30



### Mean monthly temperature (Las Trancas) vs. monthly leaf flush (Seasonal semi-deciduous TF)





### Monthly precipitation (Las Trancas) vs. monthly leaf flush (seasonal semi-deciduous TF)

### Figure 5.32



### Mean monthly relative humidity (Las Trancas) vs. monthly leaf fush (seasonal semi-deciduous TF)





Mean monthly evaporation (Las Trancas) vs. monthly leaf flush (seasonal semi-deciduous TF)

figure 5.34



### Monthly Mean Temperature (Las Trancas) vs Monthly Leaf Presence (Lomerio)

-



### Monthly Precipitation (Las Trancas) vs Monthly Leaf Presence (Lomerio)



### Monthly Mean Relative Humidity (Las Trancas) vs Monthly Leaf Presence (Lomerio)



### Monthly Mean Evaporation (Las Trancas) vs Monthly Leaf Presence (Lomerio)



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### Monthly Mean Temperature (Las Trancas) vs Monthly Leaf Senescence (Lomerio)



### Monthly Precipitation (Las Trancas) vs Monthly Leaf Senescence (Lomerio)









### Monthly Mean Evaporation (Las Trancas) vs Monthly Leaf Senescence (Lomerio)

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Figure 5.42

# Direct phenological observations of the trees Savanna Arborizada





# Monthly Mean Temperature (Las Trancas) vs Monthly Canopy Leaf Flush (Las Trancas)





# Monthly Precipitation (Las Trancas) vs Monthly Canopy Leaf Flush (Las Trancas)





# Monthly Mean Relative Humidity (Las Trancas) vs Monthly Canopy Leaf Flush (Las Trancas)





# Monthly Mean Evaporation (Las Trancas) vs Monthly Canopy Leaf Flush (Las Trancas)





# Monthly Mean Temperature (Las Trancas) vs Monthly Canopy Leaf Presence (Las Trancas)





# Monthly Precipitation (Las Trancas) vs Monthly Canopy Leaf Presence (Las Trancas)





# Monthly Mean Relative Humidity (Las Trancas) vs Monthly Canopy Leaf Presence (Las Trancas)





# Monthly Mean Evaporation (Las Trancas) vs Monthly Canopy Leaf Presence (Las Trancas)





# Monthly Mean Temperature (Las Trancas) vs Monthly Canopy Leaf Senescence (Las Trancas)





# Monthly Precipitation (Las Trancas) vs Monthly Canopy Leaf Senescence (Las Trancas)





# Monthly Mean Relative Humidity (Las Trancas) vs Monthly Canopy Leaf Senescence (Las Trancas)





# Monthly Mean Evaporation (Las Trancas) vs Monthly Canopy Leaf Senescence (Las Trancas)



# Direct phenological observations of the ground stratum Seasonally Inundated TF



# Direct phenological observations of the canopy stratum Seasonally Inundated TF



Figure 5.57





- (a) Annuli of equal area on the hemiphot, for reference only.
- (b) Annuli of equal area on the hemisphere, taking into account the area distortion of the equidistant projection.
- (c) Annuli of equal contribution from the hemisphere on to a horizontal surface allowing for area distortion (b), plus cosine correction.
- (d) Annuli of equal contribution of indirect radiation, assuming a Standard Overcast Sky and including cosine correction but ignoring area distortion (viz. the computation of Anderson 1964).
- (e) As (d) but allowing for area distortion (b).

Graph to show how the ratio of the area of an annulus on z hemiphot to the area of the corresponding zone on a hemisphere varies across the hemiphot from the centre (zenith angle 0°) to the edge (90°).



after Mitchell and Whitmore, (1991)



Figure 5.59 Annuli of Equal Area on the Hemisphere, Accounting for Distortion of the Equidistant Projection, Areal Distortion, Cosine Correction, & an Equal Contribution of Indirect Radiation





Figure 5.60



# Meteorological Variables vs. Derived Canopy Openness Lomerio (Seasonal Semi-Deciduous TF)





Hemispherical Photography Derived Canopy Openess Las Trancas (Savanna Aborizada)

Figure 5.62

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# Meteorological Variables vs. Derived Canopy Openness Las Trancas (Savanna Arborizada)











# Meteorological Variables vs. Derived Canopy Openness Chapare (Seasonally Inundated TF)




### Canopy LAI derived from Ceptometer data (Lomerio, seasonal semideciduous TF and Chapare, seasonally-inundated TF)







#### Meteorological Variables vs. Derived Canopy LAI at Lomerio & Chapare











Figure 5.68 Meteorological variables with a hydrological component vs. Ceptometer derived LAI (Lomerio, semi-deciduous TF)

Figure 5.69

#### Lomerio (Seasonal Semi-Deciduous TF) ARS-NDVI





#### Monthly Automatic Radiometry Measurements MeanVC & Maximum Value ARS-NDVI Composites Lomerio (Seasonal Semi-Deciduous TF)





#### Monthly Mean Temperature (Las Trancas) vs **ARS-NDVI** (Lomerio)



- ★ - Ground -Speamans rho - -
- 🖷 - U2 -Kendall's tau-b - -
- U1 -Pearson's & 95+% Significance (r)
- -- 🛧 - U1 -Speamans rho

- U2 -Pearson's & 95+% Significance (r)
- -- 📥 - U2 -Speamans rho
- -- = -- U1 -Kendall's tau-b



#### Monthly Precipitation (Las Trancas) vs ARS-NDVI (Lomerio)



-- 🛧 - - U1 -Speamans rho



#### Monthly Mean Relative Humidity (Las Trancas) vs ARS-NDVI (Lomerio)



- Ground -Pearson's & 95+% Significance (r)
- - 🛧 - Ground -Speamans rho
- - 🖶 - U2 -Kendall's tau-b
- --- Ground -Kendall's tau-b
  - → U2 -Pearson's & 95+% Significance (r)
- - 🛧 - U2 -Speamans rho
- -- 🖷 - U1 -Kendall's tau-b

-- 🛨 - - U1 -Speamans rho



#### Monthly Mean Evaporation (Las Trancas) vs ARS-NDVI (Lomerio)



- - 🖶 - U2 -Kendall's tau-b
- U1 -Pearson's & 95+% Significance (r)
- -- 🛧 - U1 -Speamans rho

- -- 🛧 - U2 -Speamans rho
- - 🖶 - U1 -Kendall's tau-b



Las Trancas (Savanna Arborizada) NDVI-ARS

Figure 5.75





#### Monthly Mean Temperature (Las Trancas) vs ARS-NDVI (Las Trancas)



- -----Ground1 -Pearson's & 95+% Significance (r)
- - 🛨 - Ground1 -Speamans rho
- - Tree Kendall's tau-b

- Tree -Pearson's & 95+% Significance (r)
- Ground2 -Pearson's & 95+% Significance (r)
- -- 🛨 - Tree Speamans rho
- - 🛨 - Ground2 -Speamans rho

#### Figure 5.78

#### Monthly Precipitation (Las Trancas) vs **ARS-NDVI** (Las Trancas)

	G,U-	
	0.6	
Lag (Months)	0.4	
	0.2	
	0	
-1	-0.2 0	
	-0.4	
	-0.6	
	-0.8	
and the second second second second second second second second second second second second second second second		

- Ground1 -Pearson's & 95+% Significance (r) -- - Ground1 -Kendall's tau-b
- -- \* -- Ground1 -Speamans rho
- --- Tree -Kendall's tau-b

- -- + -- Tree Speamans rho
- Ground2 -Pearson's & 95+% Significance (r) -- = -- Ground2 -Kendall's tau-b
- -- 🛧 - Ground2 Speamans rho



#### Monthly Mean Relative Humidity (Las Trancas) vs **ARS-NDVI** (Las Trancas)



- Ground1 -Pearson's & 95+% Significance (r) -- - Ground1 -Kendall's tau-b
- -- Ground1 Speamans rho
- Tree -Kendall's tau-b
- -Ground2 -Pearson's & 95+% Significance (r) --- Ground2 -Kendall's tau-b
- Tree -Pearson's & 95+% Significance (r)
- -- + -- Tree Speamans rho

-- 🛧 - - Ground2 -Speamans rho



#### Monthly Mean Evaporation (Las Trancas) vs **ARS-NDVI** (Las Trancas)



- Ground1 -Pearson's & 95+% Significance (r) -- -- Ground1 -Kendall's tau-b
- -- + -- Ground1 -Speamans rho -- = - - Tree -Kendall's tau-b

- Tree -Pearson's & 95+% Significance (r)
- -- + -- Tree -Speamans rho
- Ground2 -Pearson's & 95+% Significance (r) -- - Ground2 -Kendall's tau-b
- -- 📥 - Ground2 -Speamans rho

#### Figure 5.81

#### **Chapare (Seasonally-inundated TF) ARS Measurements**



1995 - 1996





#### Monthly Mean Temperature (Chapare) vs ARS-NDVI (Chapare)



- -- Ground Kendall's tau-b
- \* - Ground Speamans rho
- - 🖶 - U2 -Kendall's tau-b
- - 🖶 - U1 -Kendall's tau-b
- + - U2 Speamans rho
- -- 🛧 - U1 -Speamans rho



#### Monthly Precipitation (Chapare) vs **ARS-NDVI** (Chapare)



• •

- -- Ground -Kendall's tau-b .
- -- U2 -Kendall's tau-b

-- U1 -Kendall's tau-b

-- Ground -Speamans rho

--U1 -Speamans rho

-- U2 -Speamans rho - -



#### Monthly Mean Relative Humidity (Chapare) vs ARS-NDVI (Chapare)



- - 🖶 - - U2 -Kendall's tau-b

-- = -- U1 -Kendall's tau-b

★ - - U2 -Speamans rho

- 🛧 - • U1 -Speamans rho





#### Monthly Mean Evaporation (Chapare) vs ARS-NDVI (Chapare)







# Scatter plot of NDVI and GEMI for images acquired over the Chapare (seasonally-inundated TF) Field Site







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## Semi-deciduous TF: temporal trends in NOAA-14 AVHRR GEMI



#### Semi-deciduous TF: temporal trends in NOAA-14 AVHRR GEMI (15 Day Composite)



#### Figure 6.15 Semi-deciduous TF: temporal trends in NOAA-14 AVHRR GEMI (30 Day Composite)

□ +/- 30-Degrees MVC

△ +/- 30-Degrees mean


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#### Figure 6.16 Savanna Aborizada: temporal trends in the NOAA-14 AVHRR SAVI



### Savanna Aborizada: temporal trends in NOAA-14 AVHRR SAVI



□ +/- 30Degrees MVC Δ +/- 30-Degrees mean



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AVHRR SAVI (L=0.5)

#### Savanna Aborizada: temporal trends in NOAA-14 AVHRR SAVI (30 Day Composite)

Figure 6.19







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Figure 6.23





**AVHRR GEMI** 

### Savanna Aborizada: temporal trends in NOAA-14 AVHRR GEMI<sup>Figure 6.25</sup> (5 Day Composite)



Savanna Aborizada: temporal trends in NOAA-14 AVHRR GEMI<sup>Figure 6.26</sup>

**AVHRR GEMI** 







## Seasonally-inundated TF: temporal trends in NOAA-14 AVHRR SAVI

Figure 6.29



Figure 6.30 Seasonally-inundated TF: temporal trends in NOAA-14 AVHRR SAVI

.



□ +/- 30-Degrees MVC △ +/- 30-Degrees mean





□ +/- 30-Degrees MVC ▲ +/- 30-Degrees mean









#### Seasonally-inundated TF: temporal trends in NOAA-14 AVHRR GEMI Figure 6.37 (5 Day Composite)



# Seasonally-inundated TF: temporal trends in NOAA-14 AVHRR GEMI Figure 6.38





Figure 6.40 Monthly composite NDVI, tropical forest, seasonal TF (*caatinga*) and Savanna compared, Batista *et al.* (1997)

#### Seasonal semi-deciduous TF: temporal trends in Mean Local Image Euclidean Distance (SAVI; L=0.5)

++/- 10-Degrees Nadir X+/- 20-Degrees Nadir ♦ +/- 30-Degrees Nadir



1995-1996



#### Seasonal semi-deciduous TF: temporal trends in Mean Local Image Variance (SAVI; L=0.5)

++/-	10-Degrees	Nadir
<b>X+/-</b> 2	20-Degrees	Nadir
♦+/- :	30-Degrees	Nadir





++/- 10-Degrees Nadir	
×+/- 20-Degrees Nadir	
♦ +/- 30-Degrees Nadir	





#### Seasonal semi-deciduous TF: temporal trends in Mean Local Image KURTOSIS (SAVI; L=0.5)

++/- 10-Degrees Nadir
×+/- 20-Degrees Nadir
♦ +/- 30-Degrees Nadir







#### Savanna Aborizada: seasonal trends in Mean Local Image Mean Euclidean Distance (SAVI; L=0.5)







#### Seasonal semi-deciduous TF: temporal trends in Mean Local Image Variance (SAVI; L=0.5)

 ++/- 10-Degrees Nadir	
×+/- 20-Degrees Nadir	
♦ +/- 30-Degrees Nadir	



#### Seasonal semi-deciduous TF: temporal trends in Mean Local Image SKEWNESS (SAVI; L=0.5)







Seasonal semi-deciduous TF: temporal trends in

++/- !0-Degrees Nadir





Comparison of adjacent area-SAVI (L=0.5) and mean image kurtosis

#### Seasnally-inundated TF: temporal trends in Mean Local Image Euclidean Distance (SAVI; L=0.5)

+ +/- 10-Degrees Nadir X +/- 20-Degrees Nadir ♦ +/- 30-Degrees Nadir

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Figure 6.52

# Seasnally-inundated TF: temporal trends in Variance Mean Local Image Variance (SAVI; L=0.5)

++/- !0-Degrees Nadir	
×+/- 20-Degrees Nadir	
♦ +/- 30-Degrees Nadir	





# Seasnally-inundated TF: temporal trends in Mean Local Image SKEWNESS (SAVI; L=0.5)





Figure 6.54

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# Seasnally-inundated TF: temporal trends in Mean Local Image KURTOSIS (SAVI; L=0.5)

++/- 10-Degrees Nadir
×+/- 20-Degrees Nadir
♦ +/- 30-Degrees Nadir





















Meteorological variables vs. Lomerio (Seasonal semi-deciduous TF) adjacent area MLIV



- --- Relative Humidity vs. Lomerio MLIV

--- Evaporation vs. Lomerio MLIV

Water Balance vs. Lomerio MLIV









1995 - 1996

## Figure 7.4 Daily cumulative Precipiation and SAVI (L=0.5; +/- 30 degrees from nadir), Lomerio (Seasonal Semi-Deciduous TF)



## Meteorological variables vs. Las Trancas (Savanna Aborizada) adjacent area-SAVI (+/-10, 20 and 30-degrees from nadir)



# Meteorological variables vs. Las Trancas (Savanna Aborizada) adjacent area MLIV



- Mean Temperature vs. Las Trancas MLIV
- Precipitation vs. Las Trancas MLIV
- Relative Humidity vs. Las Trancas MLIV
- Evaporation vs. Las Trancas MLIV ---
  - Water Balance vs. Las Trancas MLIV











 Mean Temperature vs.	<b>Chapare SAVI</b>	(10-Degrees +/- Nadir)
Drasinitation us Chang	000 CAV/ (10 De	areas I/ Madia)

- Mean Temperature vs. Chapare SAVI (10-Degrees +/- Nadir)
  Precipitation vs. Chapare SAVI (10-Degrees +/- Nadir)
  Relative Humidity vs. Chapare SAVI (10-Degrees +/- Nadir)
  Evaporation vs. Chapare SAVI (10-Degrees +/- Nadir)
  Water Balance vs. Chapare SAVI (10-Degrees +/- Nadir)
  Mean Temperature vs. Chapare SAVI (20-Degrees +/- Nadir)
  Precipitation vs. Chapare SAVI (20-Degrees +/- Nadir)
  Relative Humidity vs. Chapare SAVI (20-Degrees +/- Nadir)
  Relative Humidity vs. Chapare SAVI (20-Degrees +/- Nadir)
  Relative Humidity vs. Chapare SAVI (20-Degrees +/- Nadir)
  Evaporation vs. Chapare SAVI (20-Degrees +/- Nadir)
  Water Balance vs. Chapare SAVI (20-Degrees +/- Nadir)
  Mean Temperature vs. Chapare SAVI (30-Degrees +/- Nadir)
  Mean Precipitation vs. Chapare SAVI (30-Degrees +/- Nadir)
  Relative Humidity vs. Chapare SAVI (30-Degrees +/- Nadir)
  Water Balance vs. Chapare SAVI (30-Degrees +/- Nadir)
  Water Balance vs. Chapare SAVI (30-Degrees +/- Nadir)
  Water Balance vs. Chapare SAVI (30-Degrees +/- Nadir)
  Water Balance vs. Chapare SAVI (30-Degrees +/- Nadir)
  Water Balance vs. Chapare SAVI (30-Degrees +/- Nadir)







Data Extrapolated

Cumulative Daily Precipiation and SAVI (L=0.5; +/- 30 degrees from nadir), Chapare (Seasonally Inundated Tropical Forest)







Leaf-Fall (Gms m-2)



Canopy Openness (%)



Ground ARS Normalised Dfference Reflectance

Figure 7.18 Las Trancas SAVI vs. Canopy Openness







Ground-1 ARS Normalised Difference Reflectance



Ground-2 ARS Normalised Difference Reflectance

Figure 7.20 Las Trancas SAVI vs. ARS-NDVI Ground-2

Figure 7.21 Chapare SAVI vs. Litterfall



Log Leaf-Fall (Gms m-2)



Canopy Openness (%)



First Pricipal Component of All Ground Phenological Observations Monitored at Each Verification Site





- - PC1 +/- 30-Degrees Nadir (Least Squares) - -



- - - PC2 +/- 30-Degrees Nadir (Least Squares) - - - PC1 +/- 30-Degrees Nadir (Least Squares)







Figure 7.30 Effectiveness of ground monitoring techniques in characterising spectral phenology



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Figure 8.1 The effectiveness of spectral phenology for characterising biological phenological changes in tropical vegetation communities

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