VULNERABILITY OF THE MINAS GERAIS LANDSCAPE TO GLOBAL CHANGES: AN INITIAL STEP TO A BOTTOM-UP APPROACH

JOÃO PAULO RODRIGUES ALVES DELFINO BARBOSA

2008

JOÃO PAULO RODRIGUES ALVES DELFINO BARBOSA

VULNERABILITY OF THE MINAS GERAIS LANDSCAPE TO GLOBAL CHANGES: AN INITIAL STEP TO A BOTTOM-UP APPROACH

Tese apresentada à Universidade Federal de Lavras como parte das exigências do Curso de pós-graduação em Agronomia, área de concentração em Fisiologia Vegetal, para a obtenção do título de "Doutor".

Orientadora

Profª. Drª. Angela Maria Soares

LAVRAS

MINAS GERAIS - BRASIL

2008

Ficha Catalográfica Preparada pela Divisão de Processos Técnicos da Biblioteca Central da UFLA

Barbosa, João Paulo Rodrigues Alves Delfino.
Vulnerability of the Minas Gerais landscape to global changes: an initial step to a bottom-up approach / João Paulo Rodrigues Alves Delfino Barbosa. – Lavras : UFLA, 2008.
193 p. : il.

Tese(Doutorado) – Universidade Federal de Lavras, 2008.
Orientador: Angela Maria Soares.
Bibliografia.

1. Leaf traits. 2. Ecosystem Functioning. 3. Land cover structure. 4. Fire regime. 5. Weather variability. 6. Extreme episodes.
I. Universidade Federal de Lavras. II. Título.
CDD – 551.5775

JOÃO PAULO RODRIGUES ALVES DELFINO BARBOSA

VULNERABILITY OF THE MINAS GERAIS LANDSCAPE TO GLOBAL CHANGES: AN INITIAL STEP TO A BOTTOM-UP APPROACH

Tese apresentada à Universidade Federal de Lavras como parte das exigências do Curso de Pós-graduação em Agronomia, área de concentração em Fisiologia Vegetal, para a obtenção do título de "Doutor".

APROVADA em 11 de Julho de 2008

Pesq. Dr. Serge Rambal	DREAM / CEFE / CNRS
Pesq. Dr. Florent Mouillot	DREAM / IRD / CEFE / CNRS
Pesq[a]. Dr[a]. Cláudia Rita de Souza	EPAMIG / Uva e Vinho
Pesq[a]. Dr[a]. Sílvia Nazaré Monteiro Yanagi	DEG / UFLA

Prof[a]. Dr[a]. Angela Maria Soares

DBI / UFLA

(Orientadora)

LAVRAS
MINAS GERAIS – BRASIL
2008

“Pelo sopro de Deus se dá a geada, e as largas águas se congelam, também de umidade carrega as densas nuvens, nuvens que espargem os relâmpagos. Então elas, segundo o rumo que Ele dá, se espalham para uma e outra direção, para fazerem tudo que lhes ordena sobre a redondeza da Terra. E tudo isso faz Ele vir para disciplina, se convém à terra, ou para exercer a Sua misericórdia.” (Jó 37: 10-13). **Obrigado, Senhor, pelas maravilhas da Sua criação!** *“Ó profundidade da riqueza, tanto da sabedoria como do conhecimento de Deus! Quão insondáveis são os Teus juízos e quão inescrutáveis os Seus caminhos! Quem, pois, conheceu a mente do Senhor? Ou quem foi o Seu conselheiro? Ou quem primeiro Lhe deu a Ele para que Lhe venha a ser restituído?”* **A Jesus Cristo, meu Senhor e Salvador, tudo dedico e tudo ofereço** *“porque Dele e por meio Dele e para Ele são todas as coisas. A Ele, pois, a glória eternamente. Amém” (Romanos 11: 33-36).*

“By the breath of God ice is given, and the broad waters are frozen. Also with moisture He saturates the thick clouds; He scatters His bright clouds. And they swirl about, being turned by His guidance, that they may do whatever He commands them on the face of the whole Earth. He causes it to come, whether for correction, or for His land, or for mercy.” (Job 37: 10-13). **Tanks, Lord for the beauty of Your creation!** *“Oh, the depth of the riches both of the wisdom and knowledge of God! How unsearchable are His judgments and His ways past finding out! For who has known the mind of the Lord? Or who has become His counselor? Or who has first given to Him and it shall be repaid to him?”* **I offer and dedicate everything to Jesus Christ, my Lord and Savior,** *“for of Him and through Him and to Him are all things, to whom be glory forever. Amen.” (Romans 11: 33-36).*

AGRADECIMENTOS

Ao SENHOR Jesus Cristo, por tudo e por todas as coisas.

À Universidade Federal de Lavras, pelas oportunidades de formação profissional, e à Coordenação de Aperfeiçoamento de Pessoal de Ensino Superior (CAPES) pela concessão de bolsas de estudo no Brasil e no exterior.

À minha orientadora, Profª. Angela Maria Soares, pela confiança, amizade, oportunidades, motivação e valiosos ensinamentos. E às pesquisadoras Helena, Sílvia e Cláudia pelo apoio na finalização da tese, pelas sugestões e trocas de experiências. E a Regina, pelas agradáveis aulas de francês.

Aos demais professores do setor de Fisiologia Vegetal/DBI/UFLA, Luiz Edson, Renato, Amauri, Donizeti, Evaristo, Marcelo e Chalfun, pelo apoio e conhecimentos transmitidos. E aos funcionários Izonel, Tanhã, Joel, Lena, Odorêncio, Barrinha e Celen pela diligência, presteza e companheirismo.

A todos os colegas de pós-graduação em Fisiologia Vegetal pela amizade e suporte durante o doutorado, especialmente Cecílio, Giordane, Emanuela Lisandro, Carlos Vinicio, Luciano, Alessandro, Teresa e Joeferson. Aos meus amigos André e Raquel pelo auxílio na finalização da tese.

Ao Laboratório de Geoprocessamento da Empresa de Pesquisa Agropecuária de Minas Gerais (Geosolos-EPAMIG), ao Laboratório de Estudos em Manejo Florestal (LEMAF-UFLA) do DCF, ao professor João José do DCS e ao colega Tiago, pelo fornecimento de dados.

Ao *Centre d'Ecologie Fonctionnelle et Evolutive* - *Centre National de la Recherche Scientifique* (CEFE-CNRS), por abrir as portas para o estágio e por todo o suporte de infra-estrutura na França. A todos os membros da equipe *Dynamique Réactionnelle des Écosystèmes, Analyse spatiale et Modélisation* (DREAM), pela recepção, amizade e ensinamentos durante o período de estágio, especialmente a Serge Rambal, Florent Mouillot e Jean-Pierre Ratte pelos esforços na realização desse trabalho e pela amizade.

A Beatrix Reynaud e sua família, a todos os colegas de "pensão", à Rose-Marie e David; Jean-Marc Orcival, e aos irmãos da *Église Evangelique "Venez-à-moi"* por me acolherem tão cordialmente em sua casa *à Montpellier*.

A todos irmãos da Aliança Bíblica Universitária (ABU), da II Igreja Presbiteriana e da Assembléia de Deus, em Lavras, pelas orações e amizade. Ao Rildo, Alessandra, D. Sônia, Rodrigo, Éderson, Marcelo e Cecílio, por serem verdadeiros irmãos, na comunhão da família de Deus. Mais ainda ao Sr. Cláudio, D. Carmem e Tiago, pelo carinho, apoio e bençãos. A minha querida noiva Ana Carolina, pela compreensão, cumplicidade, amor e amizade incondicionais. Por sempre se dispor ao meu lado e por me completar graciosamente.

Aos meus avós, Odilon, Agnelo (*in memoriam*), Margarida, Aparecida e Ticaca, e aos meus pais, José e Fátima, pelo zelo, carinho, exemplo, apoio, ensinamentos, amor, educação e pela base de vida. Aos meus irmãos: Zeca, Mela, Tize e Ronilson, e à pequenina Mariana, pelo companheirismo e cumplicidade, por sempre me motivarem para todas as empreitadas dessa vida. Aos meus tios, primos e amigos, especialmente ao Tales e Sato, pela amizade, e preciosa convivência, compartilhando alegrias e me suportando nas angústias.

A todos que contribuíram de alguma forma para a realização deste trabalho.

MEU MUITO OBRIGADO!!

J'aimerais bien remercier le Centre d'Ecologie Fonctionnelle et Evolutive - Centre National de la Recherche Scientifique (CEFE-CNRS) de Montpellier, France, pour l'accueil pendent mon séjour et pour ouvrir les portes à la réalisation de ce travail. Je remercie aussi tous les membres de l'équipe Dynamique Réactionnelle des Écosystèmes, Analyse spatiale et Modélisation (DREAM) pour les enseignements, le support et l'amitié. Je remercie spécialement mes amis Serge Rambal, Florent Mouillot et Jean-Pierre Ratte pour tous les efforts qu'ils on fait pour la conclusion de ce travail.

MERCI BEAUCOUP À TOUS!!

SUMMARY

LIST OF TABLES

LIST OF FIGURES

CHAPTER III

CHAPTER IV

CHAPTER V

CHAPTER VI

LIST OF SYMBOLS AND ABBREVIATIONS

Where appropriate, typical units are indicated in parentheses.

	Descripition
A	leaf net photosynthetic rate (μmol m^{-2} s^{-1})
A1B	climatic scenario balanced across energy sources
alt	altitude (m)
An	anomaly of precipitation or mean air temperature
A_{NFI} CNRM	fire occurence anomaly based on climatic risk of the CNRM-CM3 weather dataset
A_{NFI} CRU	fire occurence anomaly based on climatic risk of the CRU TS 2.1 weather dataset
A_{NFI} WS	fire occurence anomaly based on climatic risk of the Minas Gerais weather stations dataset
ANOVA	standard analysis of variance
A_{prec}	precipitation anomaly (mm)
$A_{prec}max$	maximum anomaly of precipitation, calculated from the 75^{th} -90^{th} percentile of the normal distribution of anomalies (mm)
$A_{prec}mim$	minimum anomaly of precipitation, calculated from the 10^{th} – 25^{th} percentile of the normal distribution of anomalies (mm)
As	amplitude of seasons derived from remotely sensed time-series
A_{temp}	temperature anomaly (^{o}C)
$A_{temp}max$	maximum anomaly of temperature, calculated from the 75^{th} -90^{th} percentile of the normal distribution of anomalies (^{o}C)
$A_{temp}mim$	minimum anomaly of temperature, calculated from the 10^{th} – 25^{th} percentile of the normal distribution of anomalies (^{o}C)

ATSR	Along Track Scanning Radiometer
CH	canopy height (m)
Ci Ca^{-1}	leaf carboxilation efficiency, the sub-stomatal carbon to atmosphere carbon rate (ppm ppm^{-1})
CNRM-CM3	Centre National de Recherches Météorologiques – Climate Model 3
CONAB	Companhia Nacional de Abastecimento
CPTEC	Centro de Previsão do Tempo e Estudos Climáticos
CRU TS 2.1	Climate Research Unit Time-series 2.1
Cwa	Köppen's classification of the climate in Minas Gerais
D	density of stems per hectare (stems ha^{-1})
E	leaf transpiration rate (mmol m^{-2} s^{-1})
ENSO	El Niño southern oscillation
f_1	influence of minimum temperature on specific maximum conversion efficiency: 0 to 1
f_2	influence of leaf-to-air vapor pressure deficit on specific maximum conversion efficiency: 0 to 1
Fapar	fraction absorbed of the incident photosynthetically active radiation by the vegetation canopy
Ff_{ij}	fire frequency in a given time (i) in a given grid cell (j)
$Ffmax_j$	maximum fire frequency observed in the analysis period at the respective grid cell under analysis
GCM	global circulation model
Geosolos-EPAMIG	Laboratório de Geoprocessamento da Empresa de Pesquisa Agropecuária de Minas Gerais
GIMMS	Global Inventory Modeling and Mapping Studies
GPP	gross primary production (g CO_2 m^{-2} day^{-1})
IBGE	Instituto Brasileiro de Geografia e Estatística

IJI	interspersion & juxtaposition index (%)
INMET	Instituto Nacional de Meteorologia
INPE	Instituto Nacional de Pesquisas Espaciais
IPCC	Intergovernmental Panel on Climate Change
LAI	leaf area index (m^2 m^{-2})
lat	latitude
LEMAF-UFLA	Laboratório de Estudos em Manejo Florestal da Universidade Federal de Lavras
long	longitude
LPI	landscape patch index (%)
LS	length of the dry season derived from the remote sensed time-series (days)
LSWI	land surface water index
MODIS	Moderate Resolution Imaging Spectroradiometer
MSEI	modified Simpson's evenness index
NDVI	normalized difference vegetation index
NFI	normalized fire index
$NFIp_{max}$	anomaly of the normalized fire index calculated as a function of the maximum precipitation anomalies
$NFIp_{min}$	anomaly of the normalized fire index calculated as a function of the minimum precipitation anomalies
$NFIt_{max}$	anomaly of the normalized fire index calculated as a function of the maximum temperature anomalies
$NFIt_{min}$	anomaly of the normalized fire index calculated as a function of the minimum temperature anomalies
NLSI	normalized landscape shape index
N_mV	average temperature (^oC) or precipitation (mm) of the month m, from 1961 to 1990 (normal value of the month m)

NOAA	National Oceanic and Atmospheric Administration
O_bV	average temperature (^oC) or precipitation (mm) observed in a given period
P	precipitation (mm)
PAR	incident photosynthetically active radiation (MJ m^{-2})
PD	patch density (patches $100ha^{-1}$)
PL	percentage of landscape (%)
RD	rooting depth (m)
RWC	relative soil water content
Sd	stress duration (days)
Si	stress intensity
SLA	specific leaf area (m^2 kg^{-1})
T	mean air temperature (^oC)
T_{min}	minimum temperature (^oC)
TRMM	Tropical Rainfall Measuring Mission satellite
UFLA	Universidade Federal de Lavras
UNEP	United Nations Environment Programme
USDA	United States Department of Agriculture
VPD	leaf to atmosphere vapor pressure deficit (kPa)
WS	weather stations in Minas Gerais
WUE	Instantaneous leaf water use efficiency
	(μmol CO_2 [mmol H2O]$^{-1}$)
Ψmax	maximum leaf water potential (MPa)
Ψmin	minimum leaf water potential (MPa)
ε	light use efficiency to fixed carbon (g C MJ^{-1} of incident photosynthetically active radiation)

ε_{max}	specific maximum conversion efficiency
ρ_{NIR}	near infrared band from MODIS (841–875 nm)
ρ_{R}	red band from MODIS (620-670nm)
ρ_{SWIR}	shortwave infrared band from MODIS (1628–1652 nm)

GENERAL ABSTRACT

BARBOSA, João Paulo Rodrigues Alves Delfino. **Vulnerability of the Minas Gerais landscape to global changes:** an initial step to a bottom-up approach. 2008. 193 p. Thesis (Doctor in Agronomy/Plant Physiology) – Federal University of Lavras, Lavras. *

In the last century, the mean air temperature in Minas Gerais increased 1.4^{o}C and the prediction is that the value will rise to almost 3^{o}C at the end of the present century. Together with this warming trend, alterations in the timing and amount of precipitation are also forecasted. This scenario can have an effect on the biochemical and biophysical processes of the landscape, affecting the vegetation functioning, with potential impacts over ecosystems services. This study was an initial step towards the assessment of the vulnerability of the landscape of Minas Gerais to the global changes, in a bottom-up perspective, by the evaluation of the interactions of weather variability with the functional characteristics of three ecosystems: Cerrado, Coffee plantations and eucalypt plantations, in three regions of Minas Gerais: South, West and North. To accomplish this major objective, we first characterized the spatial distribution of recent-past, present and future patterns of temperature and precipitation in Minas Gerais. Second, we integrated the weather information with fire regime data, to verify and predict the susceptibility of fire-prone vegetation to extreme events. We also examined the land cover structure in the study sites. The third step was the investigation of ecosystem functioning by remotely sensed vegetation indices, as well as the functioning at leaf level by a literature survey. Finally, we proposed insights on the assessment of the vulnerability of the landscape of Minas Gerais to drought stress, based on sensitivity of functional parameters to water availability. Although some limitations in the analytic procedure, this study could represent one of few large-spectrum surveys of climate change effects on ecosystem functioning in Minas Gerais, ranging from leaf to landscape. Moreover, we generated a database and proposed a framework based on sensitivity analysis that allowed insights on landscape vulnerability to climate changes and scaling procedures. This database can be used further in more complex simulation modeling of landscape dynamics in diverse time-space scales. The proposed framework could represent a component of the strategy to understand and anticipate the potential effects of global changes on Minas Gerais landscape.
Key-words: weather variability, leaf traits, ecosystem functioning, fire regime, land cover structure, extreme episodes.

---

* Guidance Committee: Prof. Dr. Angela Maria Soares (Adviser), Dr. Serge Rambal - CEFE/CNRS (Co-adviser).

RESUMO GERAL

BARBOSA, João Paulo Rodrigues Alves Delfino. **Vulnerabilidade da paisagem de Minas Gerais às mudanças globais:** um passo inicial para uma abordagem tipo *bottom-up*. 2008. 193 p. Tese (Doutorado em Agronomia / Fisiologia Vegetal) – Universidade Federal de Lavras, Lavras.*

A temperatura média do ar no estado de Minas Gerais aumentou 1,4°C, em relação aos valores normais, no século passado. As previsões para o século XXI apontam um aumento de até 3°C e alterações nos padrões de distribuição e na quantidade das chuvas. Esse cenário poderá afetar a paisagem, por efeitos diretos e indiretos do clima sobre a fisiologia das plantas, com impactos potenciais sobre os serviços dos ecossistemas. Esse trabalho representa um passo inicial para estudar a vulnerabilidade da paisagem de Minas Gerais às mudanças globais, numa perspectiva tipo *bottom-up*, relacionando a variabilidade climática e as características ecofisiológicas de três ecossistemas (cafezal, cerrado e eucaliptal) em três regiões do estado (norte, sul e oeste). A primeira etapa do estudo consistiu na caracterização dos padrões da distribuição espacial de temperatura do ar e precipitação no passado, presente e futuro. Em seguida, essa informação foi integrada à análise do regime de queimadas, no espaço e no tempo, para verificar e predizer a susceptibilidade da vegetação ao fogo em condições extremas. A estrutura da cobertura da terra também foi analisada. A terceira etapa consistiu na análise do funcionamento dos ecossistemas, por sensoriamento remoto, e da folha, por uma revisão bibliográfica. Finalmente, a vulnerabilidade da paisagem ao estresse hídrico foi abordada através de equações de sensibilidade de características fisiológicas à disponibilidade hídrica no solo. Apesar de limitações, esse estudo agrupou várias informações relacionadas aos efeitos das mudanças climáticas sobre os ecossistemas de Minas Gerais, da folha à paisagem. Além disso, foram gerados um banco de dados e uma estrutura para análise, que permitem direcionar estudos ecofisiológicos para acessar a vulnerabilidade. Essas informações poderão ser utilizadas para simulações mais complexas, em exercícios de mudança de escala e para a modelagem da dinâmica da paisagem, podendo representar um componente dentro da complexidade da estratégia para compreender e antecipar impactos potenciais das mudanças globais na paisagem de Minas Gerais.

Palavras-Chave: variabilidade climática, características foliares, funcionamento de ecossistemas, queimadas, uso da terra, eventos extremos.

---

* Comitê Orientador: Prof[a]. Dr[a]. Angela Maria Soares (Orientadora), Dr. Serge Rambal - DREAM/CEFE/CNRS (Co-orientador).

CHAPTER I

Background and Organization

1 GENERAL INTRODUCTION

The global climate is unequivocally changing as a consequence of increasing atmospheric concentrations of greenhouse gases, which are mediating the air and ocean warming documented on continental and regional scales (Solomon, 2007). Widespread episodes of drought, heavy precipitation, heat waves and tropical cyclones have been reported as a consequence of global warming (Rosenzweig et al., 2004; Slingo et al., 2005; Verdin et al., 2005). The effects of these climatic trends on terrestrial ecosystems have already been noted, although the potential consequences are still in doubt (Hurtt et al., 1998; Walther et al., 2002; Root et al., 2003; Cardoso et al., 2003; Nepstad et al., 2004; Hulme, 2005; Metzger et al., 2006; Smith & Wandel, 2006; Solomon, 2007).

Among some possible consequences, there is a consensus that climatic changes will be responsible for the loss of biodiversity, large scale fires, and decrease in food production as well as a loss of other ecosystems services. However, the degree of these impacts can vary among diverse ecosystems, because the responses depend on complex interactions between direct and indirect impacts on plant physiology, consequently on ecosystems functioning, and finally on landscape dynamics, characterizing a bottom-up sense of the response stream (Figure 1). In this context, nowadays the climatic changes may be one of the major threats to ecosystems, and their vulnerability to climatic changes can be described as a function of the physiological sensitivity to extreme episodes and adaptive capacity to future climate variability (Watson et al., 2000; UNEP, 2002; Hulme, 2005; Chartzoulakis & Psarras, 2005; Tjoelker & Zhou, 2007).

Vulnerability is the degree to which a system, subsystem or system component is susceptible to, or unable to cope with adverse effects like harm due to exposure to a hazard, either a perturbation or stress-stressor, including climate variability and extreme episodes. Although such a definition addresses environmental factors, it already includes some vegetation characteristics, such as susceptibility, which is a function of exposure, sensitivity, resilience and adaptive capacity or plasticity (Turner et al., 2003; Gallopín, 2006; Metzger et al., 2006; Smith & Wandel, 2006; Pielke Junior et al., 2007) (Figure 2).

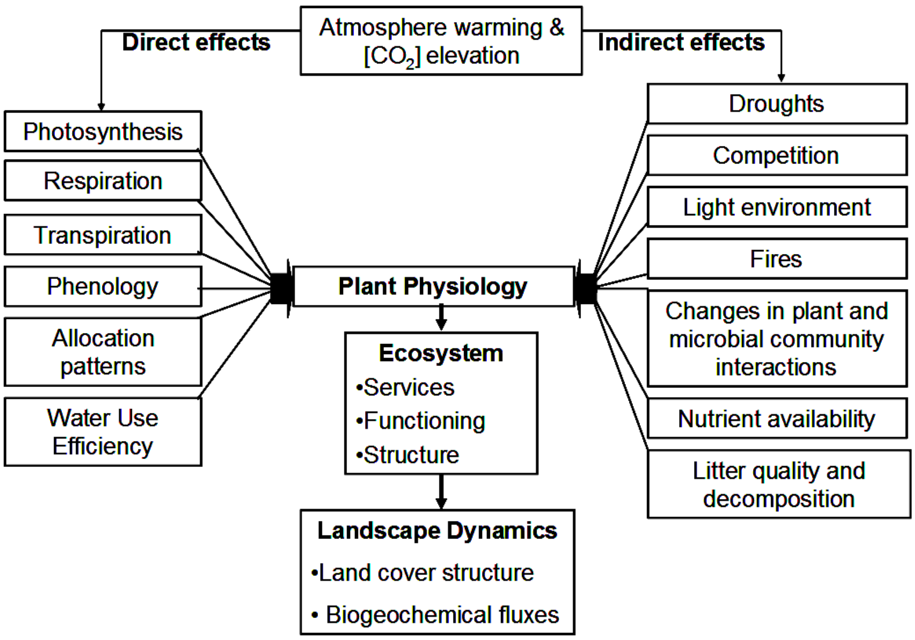

Figure 1 - The major factors affecting plant physiological responses to the effects of global changes in terrestrial ecosystems.

It is important to notice that vulnerability is registered not only by exposure to perturbations and stresses, but also must include the capacity to deal with variables of the human–environment systems. This perspective builds toward the sustainability concept, which links, in a diverse and complex way, the dual objectives of meeting the needs of society while sustaining the life support processes of the ecosystems (Turner et al., 2003; Gallopín, 2006). The sustainability and vulnerability themes enlarge, and redirect the focus on plant physiology studies on two main issues: to understand the sensibility and resilience of functional properties to environmental drivers, and to study the complex mechanisms that vegetation has to cope with and to adapt to stress situations, at diverse time-space scales.

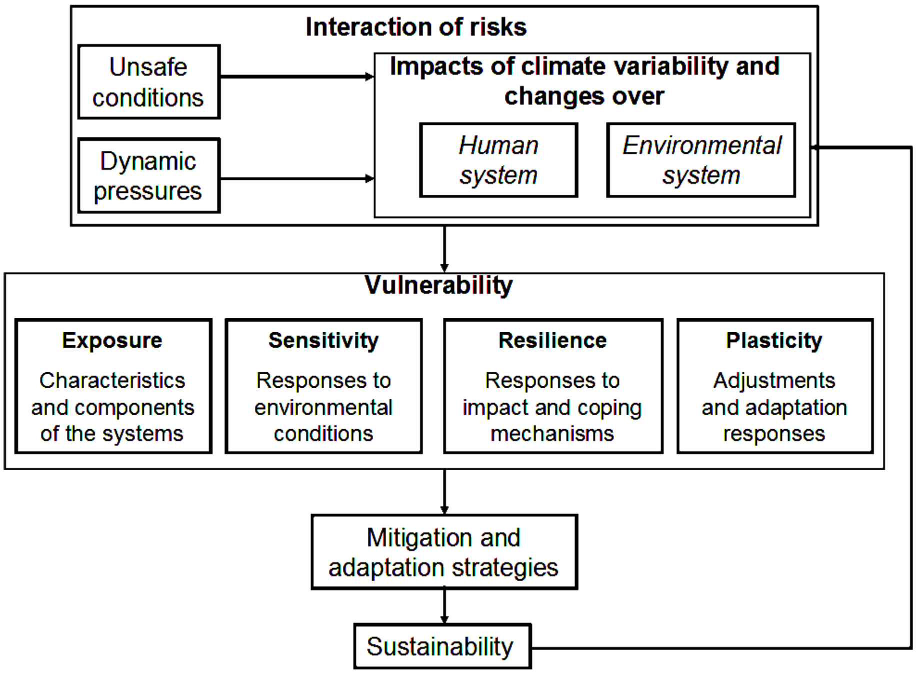

Figure 2 – A framework to illustrate the vulnerability concept.

The ecophysiological tools can be used in both issues together with other disciplines to solve this complexity. First: linking studies at the leaf level with remote sensing techniques and simulation modeling, in the up and downscaling procedures of functional processes. Second: coupling physiological and climate models to simulate landscape dynamics in the future climate scenarios and under extreme episodes. Third: evaluating potential risks and impacts as well as feedback responses of vegetation to atmospheric properties.

Those three aspects could be useful to establish mitigation strategies in areas where the human-environment system is vulnerable to climate extremes.

Based on these assumptions, we composed an initial step to a bottom-up approach to the analysis of vulnerability to climatic changes in the landscape of Minas Gerais, through studies of plant physiology related to meteorological and ecological characteristics. In this initial step, plant functioning, at diverse levels, was place-based and the weather variability was the forcing factor able to disturb the normal landscape conditions by affecting the plant physiology. The greatest challenge was to work with, and integrate, a variety of information at different scales of time and space. We expect that the results of this exercise will inspire further research with similar subjects and motivate interdisciplinary approaches in other case studies in Brazil.

2 HYPOTHESES, PROBLEM DEFINITION AND QUESTIONS

We postulated that the rising concentration of greenhouse gases in the atmosphere will alter the climatic system in Minas Gerais, not only by increasing air temperature, but also by modifying regional patterns of wind speed, evapotranspiration, precipitation and radiation. These alterations would result in more frequent, intense and longer episodes of drought, threatening the landscape processes by increasing the flammability and affecting the energy, carbon and water fluxes of the ecosystems (Figure 3) (Canziani et al, 2001; Dai et al., 2001; Davidson et al., 2001; Mouillot et al., 2002; Cardoso et al., 2003; Nepstad et al.; 2004; Hulme, 2005; Bondeau et al., 2007; DeLucia et al., 2007). We tested our hypothesis in three case studies on the Minas Gerais landscape: the natural cerrado vegetation (tropical savanna-like vegetation), coffee and eucalypt plantations. The analytic procedure was applied in three study regions, to verify the direct and indirect effects of drought on ecosystem functioning, fire occurrence and land cover structure in space and in time. At the landscape level, the following groups of questions were addressed to guide this thesis:

2.1. CHANGES IN LAND USE AND LAND COVER

a - What are the patterns in time and space of land use and land cover in the study sites in the landscape of Minas Gerais and how to quantify them?

b - Could one detect a relation between land cover and extreme events, such as atypical drought?

c - How can the land use patterns be associated to landscape vulnerability to climate?

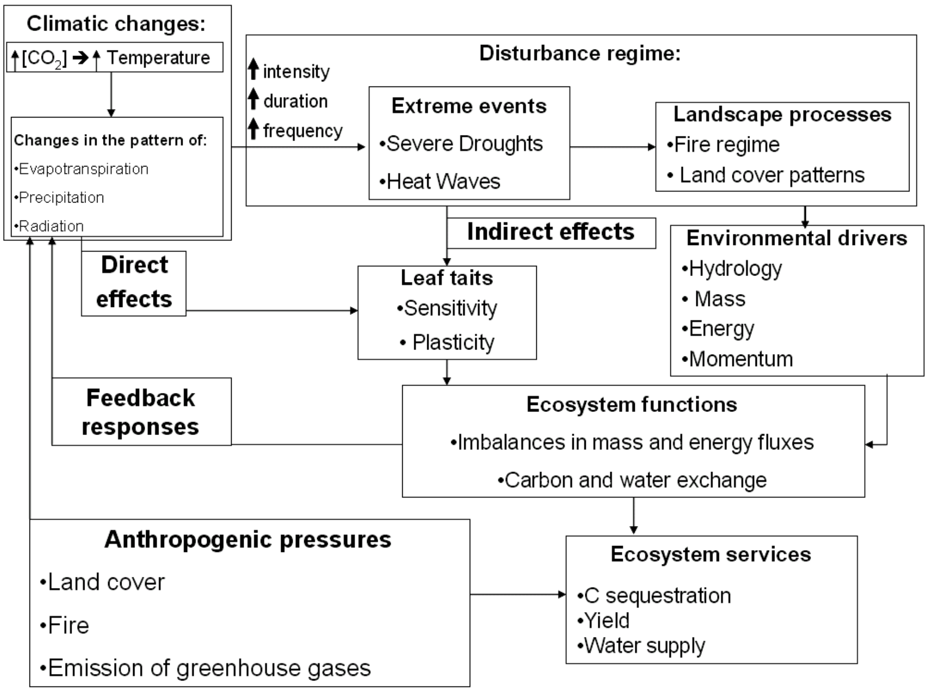

Figure 3 - A representation of possible interrelations and interactions among weather, landscape properties and leaf traits acting on the ecosystem functioning.

2.2 VULNERABILITY TO FIRE

a - How space-time fire regime over Minas Gerais is related to extreme episodes, land cover structure and anthropogenic pressures?

b - What are the possible impacts of fires on the carbon and water fluxes over Minas Gerais landscape?

c - Which systems are more vulnerable to fire in the landscape and how do they respond to this perturbation?

d - How could future climate alter the fire frequency in Minas Gerais?

2.3 FUNCTIONAL VULNERABILITY

a - Which ecosystem is more sensitive to weather variability in the landscape of Minas Gerais and why?

b - How to describe ecophysiological responses in the ecosystem and leaf level not generally involved in standard climate conditions?

c - How to link leaf traits to ecosystem functioning using the responses to water availability?

2.4 BACKGROUND AND SPECIFIC QUESTIONS ABOUT THE STUDIED ECOSYSTEMS

2.4.1 Cerrado

The Brazilian savanna biome, identified as cerrado, covered an area of more than 2 million km^2 (24% of the country) before the recent exploitation by intensive agriculture during the last 35 years. Currently, the term cerrado can describe the broad phytogeographic region or one fragment of the primary vegetation. The cerrado is often associated with strong climate seasonality, poor and deep soils and fire (Franco et al., 2005; Durigan & Ratter, 2006).

Notwithstanding these environmental limitations to plant development, cerrado vegetation contains a complex community structure, with contrasting phenological patterns and differences in the root system distribution. This complexity reflects on the resource use strategies, photosynthetic capacity and leaf structure, contributing to the functional heterogeneity in time and space (Prado & Moraes 1997; Jackson et al., 1999; Bucci et al., 2005). However, the way that cerrado vegetation could interact with climatic variability, coupling structure and function, is still uncertain. Within these considerations, the questions addressed were:

a - Among the different functional types of cerrado plants (deciduous, semideciduous, brevideciduous and evergreen species), which one could be the most sensitive to weather variability?

b - What are the space-time strategies used by cerrado plants to overcome extreme episodes and which one is the most efficient to cope with weather variability?

c - What are the ecosystem responses to climate variability in terms of carbon and water budgets?

d - What are the vulnerabilities of the cerrado ecosystem to climatic changes and what are the perspectives for the future?

2.4.2 Coffee plantation

Brazil is the first country in the rank of arabic coffee (*Coffea arabica* L.) production (36.2 million bags in 2007/08), and Minas Gerais is the most important coffee growing area in the country (45% of Brazilian production). The 2007/08 state’s yield has decreased 35% in relation to the previous year. In the south, as well as in the west of Minas Gerais, the main production areas, the reduction was estimated in 47% (5.6 million bags) (USDA, 2007).

Climatic disturbances in those regions were, probably, the cause of the decrease in coffee production. From mid-September 2006 until February 2007, there were frequent and intense rains. After the unusual wet season, the region faced a strong drought, the precipitation had decreased and the temperatures increased to values considered abnormal for the period. In the beginning of 2006, the same climatic pattern was observed, and it was assumed that the water stress caused by this anomalous drought had a negative effect on the 2007/08 coffee yield (USDA, 2007; CONAB, 2007).

As related in the CONAB's (2007) report, researchers and field technicians inputted the reduction of the coffee yield in Minas Gerais to physiological disturbances of coffee plants, as results of abnormal climatic episodes. Although those are non-experimental observations, they can indicate that coffee agriculture in Minas Gerais is vulnerable to climatic variability. The questions proposed to guide the studies to assess the vulnerability of coffee plantations on the landscape of Minas Gerais were:

a - How and how much weather variability can affect coffee yield in Minas Gerais?

b - There are differences in the vulnerability to climate of coffee plantations in different sites (south and west) of Minas Gerais?

c - What are the coffee strategies to overcome periods of severe drought?

d - What are the responses in water and carbon fluxes of coffee plantations to space-time weather variability?

e - What are the possible impacts of climatic changes on coffee agriculture in Minas Gerais?

2.4.3 Eucalypt plantations

Eucalyptus sp. has been extensively planted in Minas Gerais for reforestation as well as for cellulose, timber and energy production. Despite its economic importance, large-scale planting of this exotic species has been criticized because of reported nutrient and water depletion (Soares & Almeida, 2001; Stape et al., 2004). Information on physiological processes would be useful to improve the understanding of the functioning and dynamics of this ecosystem, and to answer the questions concerning services and resource consumption. This is a central point to adjust the management for long-term sustainability, carbon sequestration, water conservation, and also, to meet the demands of markets requiring more guarantees of environmentally-correct policies (Villa Nova et al., 2003).

One mechanism to encourage reforestation is the inclusion of cultivated forests in carbon trading schemes. Since reforestation is seen as one solution to slow the rise of atmospheric CO_2 (Solomon, 2007), it is necessary to quantify the possible effects that extreme episodes could have on the carbon balance of eucalypt plantations (Barton & Montagu, 2006). It is also important to know where the climate changes can lead, in terms of eucalypt productivity and water relations, to anticipate management consequences on the ecosystem functioning. Within those considerations, we aimed to answer the following questions, concerning the eucalypt plantations in Minas Gerais:

a - What are the space-time fluxes of water and carbon in these ecosystems and how are they influenced by environmental perturbations?

b - Could eucalypt plantations be a carbon sink and regulate mesoclimate by a feedback response on the atmospheric concentration of greenhouse gases?

c - What are the vulnerabilities of eucalypt plantations in Minas Gerais to climatic changes?

d - Are there consequences in cultivating this species on the landscape? Could this plantation be positive or negative to the environment in the future?

3 JUSTIFICATIONS

a - Approaches to predict vegetation responses to climatic change, in tropical regions, have addressed abundance or distribution effects. However, little attention has been given to the ecosystems functioning. In general, few works have tried to associate plant physiology with the concept of vulnerability or sustainability, until now.

b - Research needs to be performed, in different ecosystems, to improve the knowledge about the effects of climate on the processes by which terrestrial ecosystems take and return carbon from the atmosphere.

c - The ecophysiological concepts, tools and techniques of scaling up and down through space and time would help to identify the mechanistic bases of feedback in the biosphere that link ecosystem functions, landscape properties and weather.

d – Research, within these perspectives, on Brazilian landscapes has been somewhat restricted to the Amazonian rain forest. However, the attempt to identify the role that Brazilian ecosystems have in the global mass and energy balances has not been clearly defined, and how the climatic changes could affect these fluxes is still uncertain.

e – The results could be helpful to work out strategies able to increase the flexibility of ecosystems management, set-up mitigation strategies, enhance the adaptability of cultivated species and to study processes that will improve our knowledge on plant and ecosystem physiology in drier and warmer conditions.

4 OBJECTIVES

a – Set-up an initial step towards a bottom-up assessment of the vulnerability to global changes in Minas Gerais and establish a procedure to analyze databases of different sources and scales in relation to temperature and precipitation variability.

b - Evaluate the vulnerability of cerrado, coffee and eucalypt, in different space-time scales, to the climatic changes in the landscape of Minas Gerais.

c - Verify, in each ecosystem, which functional parameters are the most sensitive to soil moisture availability and how they can be used to describe vulnerability.

d - Develop scientific information about the responses of terrestrial ecosystems of Minas Gerais to environment that could be further used to develop and/or parameterize simulation models at the landscape level.

5 SCOPE AND ORGANIZATION

The scope of this thesis was the evaluation of the vulnerability to global changes of Minas Gerais landscape by a framework composed of three study axes. The interconnection of these axes generated information about the functional sensitivity to weather variability and patterns of landscape characteristics. The first axis comprised the characterization of environmental properties, such as climate variables and soil type. The second axis was composed of ecophysiological information at the leaf and ecosystem level. The third axis corresponded to information obtained to landscape fragmentation and fire regime (Figure 4). The thesis is arranged to describe the methodology, the main results and the discussion of these three study axes. It is organized in six chapters:

a - Chapter I: The first chapter described the background, hypothesis, justifications and questions that drove this thesis as well as the definition of the research objectives and scope.

b - Chapter II: Chapter two showed the climatic background encountered by the study and characterization of precipitation and temperature over Minas Gerais, presenting data from the recent past, current, as well as future scenarios.

c - Chapter III: This chapter brought a description of the landscape of Minas Gerais: the land cover and use and the fire regime. This information was correlated to climate parameters to set-up a climatic risk to fire occurrence.

d - Chapter IV: The aspects of ecosystems functioning and structure: the sensitivity analysis of leaf traits and remotely sensed vegetation indices to water availability and the vulnerability parameters, derived from the correlation of these data, were shown in the fourth chapter.

e - Chapter five: This chapter brought the sensitivity analysis in relation to water availability. The vulnerability parameters, derived from the correlation of these data, were also shown.

f - Chapter six: This chapter was composed of a schematic overview and a final evaluation of the main outcomes of the thesis. It brought the practical recommendations, perspectives and conclusions of this thesis.

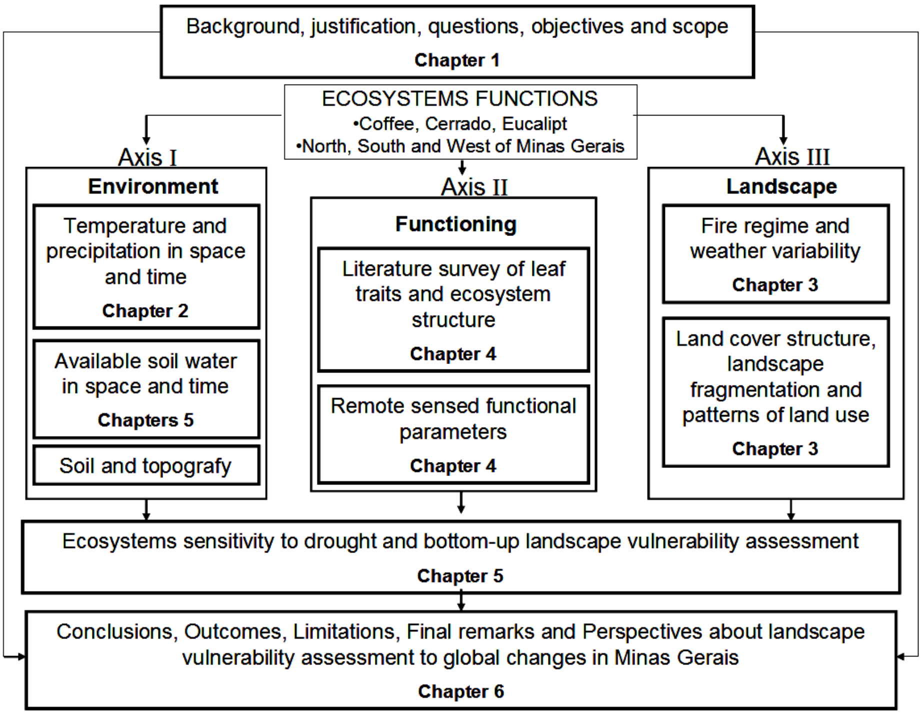

Figure 4 – Scheme representing the organization of the thesis.

6 REFERENCES

BARTON, C. V. M.; MONTAGU, K. D. Effect of spacing and water availability on root:shoot ratio in *Eucalyptus camaldulensis*. **Forest Ecology and Management**, Amsterdam, v. 221, n. 1-3, p. 52–62, Jan. 2006.

BONDEAU, A.; SMITH, P. C.; ZAEHLE, S.; SCHAPHOFF, S.; LUCHT, W.; CRAMER, W.; GERTEN, D.; LOTZE-CAMPEN, H.; MULLER, C.; REICHSTEIN, M.; SMITH, B. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. **Global Change Biology**, Oxford, v. 13, n. 3, p. 679-706, Mar. 2007.

BUCCI, S. J.; GOLDSTEIN, G.; MEINZER, F. C.; FRANCO, A. C.; CAMPANELLO, P.; SCHOLZ, F. G. Mechanisms contributing to seasonal homeostasis of minimum leaf water potential and predawn disequilibrium between soil and plant water potential in neotropical savanna trees. **Trees**, Victoria, v. 19, n. 3, p. 296-304, May 2005.

CANZIANI, O.; DOKKON, D. J.; LEARY, N. A.; WHITE, K. S.; McCARTHY, J. J. (Ed. Working Group II). **Climate Change 2001**: impacts, adaptation, and vulnerability. Cambridge: IPCC/Cambridge University, 2001a. (Third Assessment Report).

CARDOSO, M. F.; HURTT, G. C.; MOORE III, B.; NOBRE, C. A.; PRINS, E. M. Projecting future fire activity in Amazonia. **Global Change Biology**, Oxford, v. 9, n. 5, p. 656 – 669, May 2003.

CHARTZOULAKIS, K.; PSARRAS, G. Global change effects on crop photosynthesis and production in Mediterranean: the case of Crete, Greece. **Agriculture, Ecosystems and Environment**, Amsterdam, v. 106, n. 2-3, p.147–157, Apr. 2005.

COMPANHIA NACIONAL DE ABASTECIMENTO. **Segundo levantamento da safra de café 2007/2008**. 2007. Disponível em: <http://www.conab.gov.br/conabweb/download/safra/3BoletimCafe.pdf >. Acesso em: 31 out. 2007.

DAI, X.; DING, Y.; HOUGHTON, J. T.; GRIGGS, D. J.; NOGUER, M.; LINDEN, P. J.; MASKELL, K.; JOHNSON, C. A. (Ed. Working Group I). **Climate Change 2001**: the scientific basis. Cambridge: IPCC/Cambridge University, 2001. (Third Assessment Report).

DAVIDSON, O.; METZ, B.; SWART, R.; PAN, J. (Ed. Working Group III). **Climate Change 2001:** mitigation**.** Cambridge: IPCC/Cambridge University, 2001 (Third Assessment Report).

DeLUCIA, E. H.; DRAKE, J. E.; THOMAS, R. B.; GONZALEZ-MELER, M. Forest carbon use efficiency: is respiration a constant fraction of gross primary production?. **Global Change Biology**, Oxford, v. 13, n. 6, p. 1157–1167, June 2007.

DURIGAN, G.; RATTER, J. A. Successional changes in cerrado and cerrado/forest ecotonal vegetation in western São Paulo state, Brazil, 1962–2000. **Edinburgh Journal of Botany**, Edinburgh, v. 63, p. 119–130, 2006.

FRANCO, A. C.; BUSTAMANTE, M.; CALDAS. L. S.; GOLDSTEIN, G.; MEINZER, F. C.; KOZOVITS, A. R.; RUNDEL, P.; CORADIN, V. T. R. Leaf functional traits of neotropical savanna trees in relation to seasonal water deficit. **Trees**, Victoria, v. 19, n. 3, p. 326-335, May 2005.

GALLOPÍN, G. C. Linkages between vulnerability, resilience, and adaptive capacity. **Global Environmental Change**, Oxford, v. 16, n. 3, p. 293–303, Aug. 2006.

HULME, P. E. Adapting to climate change: is there scope for ecological management in the face of a global threat?. **Journal of Applied Ecology,** Oxford, v. 42, n. 5, p. 784 – 794, Oct. 2005.

HURTT, G. C.; MOORCROFT, P. R.; PACALA, S. W.; LEVIN, S. A. Terrestrial models and global change: challenges for the future. **Global Change Biology**, Oxford, v. 4, n. 5, p. 581 – 590, June 1998.

JACKSON, P. C.; MEINZER, F. C.; BUSTAMANTE, M.; GOLDSTEIN, G.; FRANCO, A. RUNDEL, P.W. CALDAS, L. IGLER, E.; CAUSIN, F. Partitioning of soil water among tree species in a Brazilian Cerrado ecosystem. **Tree Physiology**, Victoria, v. 19, n. 11, p.717-724, Sept. 1999.

METZGER, M. J.; ROUNSEVELL, M. D. A.; ACOSTA-MICHLICK, L.; LEEMANS, R.; SCHRÖTER, D. The vulnerability of ecosystem services to land use change. **Agriculture, Ecosystems and Environment**, Amsterdam, v. 114, n. 1, p. 69–85, May 2006.

MOUILLOT, F.; RAMBAL, S.; JOFFRE, R.; Simulating climate change impacts on fire frequency and vegetation dynamics in a Mediterranean-type ecosystem. **Global Change Biology**, Oxford, v. 8, n. 5, p. 423 – 437, May 2002.

NEPSTAD, D.; LEFEBVRE, P.; SILVA, U. L.; TOMASELLA, J.; SCHLESINGER, P.; SOLORZANO, L.; MOUTINHO, P.; RAY, D.; BENITO, J. G. Amazon drought and its implications for forest flammability and tree growth: a basin-wide analysis. **Global Change Biology**, v. 10, p. 704 – 717, 2004.

PIELKE JR, R. A.; ADEGOKE, J. O.; CHASE, T. N.; MARSHALL, C. H.; MATSUI, T.; NIYOGI, D. A new paradigm for assessing the role of agriculture in the climate system and in climate change. **Agricultural and Forest Meteorology**, Amsterdam, v. 142, n. 2-4, p. 234–254, Feb. 2007.

PRADO, C. H. B. A.; MORAIS, J. A. P. V. de. Photosyntetic capacity and specific leaf mass in twenty wood species of Cerrado vegetation under field conditions. **Photosynthetica**, Prague, v. 33, n. 1, p. 103-112, 1997.

ROOT, T. L.; PRICE, J, T.; HALL, K. R. Fingerprints of global warming on wild animals and plants. **Nature**, London, v. 421, n. 6918, p. 57–60, Jan. 2003.

ROSENZWEIG, C.; STRZEPEK, K. M.; MAJOR, D. C.; IGLESIAS, A.; YATES, D. N.; McCLUSKEY, A.; HILLEL, D. Water resources for agriculture in a changing climate: international case studies. **Global Environmental Change**, Oxford, v. 14, n. 4, p. 345–360, Dec. 2004.

SOLOMON, S.; QIN, D.; MANNING, M.; MARQUIS, M.; AVERYT, K.; TIGNOR, M. M. B.; MILLER JUNIOR, H. L.; CHEN, Z**.** (Ed. Working Group I) **Climate Change 2007**: the physical science basis: summary for policymakers. Paris: IPCC**,** 2007. (Fourth Assessment Report).

STAPE, J. L.; BINKLEY, D.; RYAN, M .G.; GOMES, A. N. Water use, water limitation, and water use efficiency in a *Eucalyptus* plantation. **Bosque**, Valdivia, v. 25, n. 2, p. 35-41, 2004.

SLINGO, J. M.; CHALLINOR, A. J.; HOSKINS, B. J.; WHEELER, T. R. Introduction: food crops in a changing climate. **Philosophical Transactions of the Royal Society**, London, v. 360, n. 1463, p. 1983–1989, Nov. 2005.

SMITH, B.; WANDEL, J. Adaptation, adaptive capacity and vulnerability. **Global Environmental Change**, Oxford, v. 16, n. 2, p. 282–292, May 2006.

SOARES, J. V.; ALMEIDA, A. C. Modeling the water balance and soil water fluxes in a fast growing *Eucalyptus* plantation in Brazil. **Journal of Hydrology**, Amsterdam, v. 253, n. 1-4, p.130-147, Nov. 2001.

TJOELKER, M. G.; ZHOU, X. The many faces of climate warming. **New Phytologist**, Cambridge, v. 176, n. 4, p. 739–742, 2007.

TURNER, B. L.; MATSON, P. A.; McCARTHY, J. J.; CORELL, R. W.; CHRISTENSEN, L.; ECKLEY, N.; HOVELSRUD-BRODA, G. K.; KASPERSON, J. X.; LUERS, A.; MARTELLO, M. L.; MATHIESEN, M. S.; NAYLOR, R.; POLSKY, C.; PULSIPHER, A.; SCHILLER, A.; SELIN, H.; TYLER, N. Illustrating the coupled human–environment system for vulnerability analysis: Three case studies. **Proceedings of the national Academy of Science of the United States of America,** Washington, v. 100, n. 14, p. 8080-8085, July 2003.

UNITED NATIONS ENVIRONMENT PROGRAMME. **Global Environmental Outlook:** GEO-3. London, 2002.

UNITED STATES DEPARTMENT OF AGRICULTURE, FOREIN AGRICULTURAL SERVICE. **Tropical Products:** World Markets and trade. Circular Series FTROP 2-07. 2007.

VERDIN, J.; FUNK, C.; SENAY, G.; CHOULARTON, R. Climate science and famine early warning. **Philosophical Transactions of the Royal Society**, London, v. 360, n. 1463, p. 2155–2168, Nov. 2005.

VILLA NOVA, N. A.; MOREIRA, P. R.; PEREIRA, A. B. Eficiência de captura de energia solar por dosséis de *Eucalyptus pellita* F. Muell sob várias densidades de plantio. **Revista Brasileira de Agrometeorologia**, Santa Maria, v. 11, n. 2, p. 269-274, 2003.

WALTHER, G. R.; POST, E.; CONVEY, P. Ecological responses to recent climate change. **Nature**, London, v. 416, n. 6879, p. 389–395, Mar. 2002.

WATSON, R. T.; NOBLE, I. R.; BOLIN, B.; RAVINDRANATH, N. H.; VERARDO, D. J.; DOKKEN, D. J. (Ed.). **Land use, Land use change and Forestry:** a special report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge: Cambridge University, 2000.

CHAPTER II

Analysis of the space-time variability of mean temperature and precipitation to studies of the landscape vulnerability to global changes in Minas Gerais, southeast Brazil

ABSTRACT

BARBOSA, João Paulo Rodrigues Alves Delfino. Analysis of the space-time variability of mean temperature and precipitation to studies of the landscape vulnerability to global changes in Minas Gerais, southeast Brazil. In:______. **Vulnerability of the Minas Gerais landscape to global changes:** an initial step to a bottom-up approach. 2008. Chap. 2, 193 p. Thesis (Agronomy/Plant Physiology) Federal University of Lavras, Lavras.*

An accurate regional picture of the intraseasonal-to-interannual variability of weather is a first-order requirement for the assessment of the vulnerability of the landscape to global warming. Regression analysis, variography, interpolation methods and classic variance analysis were used to characterize the recent-past, present and future patterns of mean temperature and precipitation in Minas Gerais, southeast Brazil. One global dataset (CRU TS 2.1), a dataset from a global circulation model (GCM) (CNRM-CM3) and datasets from weather stations (CPTEC-INPE and INMET weather stations) in the north, west and south of Minas Gerais were used. Monthly anomalies, from each dataset, were calculated subtracting normal values from observed values. The normal values were averaged monthly from 1961 to 1990 from each dataset. The results of this study indicated that the data from the global dataset as well as from the GCM were sensitive to the small scale patterns of climate variability in Minas Gerais, demonstrating the annual seasonality and spatial variability of temperature and precipitation, according with the weather station data. We also observed the relationships of El Niños and the occurrence of higher anomalies of temperature and small anomalies of precipitation. In general, the three datasets indicated a tendency of increment in the mean temperature and in precipitation over time. The future climate in Minas Gerais is forecasted with higher annual precipitation, concentrated in the wet season, and higher annual mean temperatures, increasing especially in the dry season. The data generated with this study should help to improve our understanding of precipitation variability in space and time over Minas Gerais, as well as to predict occurrence of extreme episodes of drought and heat waves. This information can be applied on ecological studies and to landscape modeling. Possible limitations to the use of the global dataset and GCMs downscaling to describe the weather in Minas Gerais are discussed.

Key words: weather variability, global datasets, anomalies, future scenarios.

---

* Guidance Committee: Prof. Dr. Angela Maria Soares (Adviser), Dr. Serge Rambal - CEFE/CNRS (Co-adviser).

RESUMO

BARBOSA, João Paulo Rodrigues Alves Delfino. Análise da variabilidade espaço-temporal da temperatura média e da precipitação para estudos da vulnerabilidade da paisagem às mudanças globais em Minas Gerais**.** In: ______. **Vulnerabilidade da paisagem de Minas Gerais às mudanças globais:** um passo inicial para uma abordagem tipo *bottom-up*. 2008. Cap. 2, 193 p. Tese (Agronomia / Fisiologia Vegetal) – Universidade Federal de Lavras, Lavras.*

A caracterização da variabilidade intra-sazonal e interanual do clima é um requisito de primeira ordem para estudar a vulnerabilidade da paisagem, num nível regional, em função do aquecimento global. Nesse estudo, métodos de análise de regressão, variografia, interpolação e análise de variância foram utilizados para caracterizar os padrões espaço-temporais de temperatura e precipitação no estado de Minas Gerais. Dados de uma base global (CRU TS 2.1), de um modelo de circulação global (GCM) (CNRM-CM3) e dados de estações climatológicas (CPTEC-INPE e INMET) do sul, oeste e norte de Minas Gerais foram utilizados para essa caracterização. Valores mensais de anomalias foram obtidos subtraindo-se valores normais (média mensal de 1961-1990 para cada base de dados) dos valores observados. Os resultados indicaram que dados da base global e do GCM foram sensíveis na demonstração da variabilidade sazonal e regional do clima de Minas Gerais, não diferindo dos padrões observados na base de dados das estações climatológicas. Além disso, observou-se a ocorrência de maiores valores de anomalias de temperatura e menores de precipitação durante eventos de El Niño. Em geral, as três bases de dados indicaram uma tendência de aumento nas anomalias máximas e mínimas da temperatura do ar e da precipitação ao longo do tempo. Essas tendências podem indicar que, no futuro, a precipitação anual deve aumentar, concentrando-se na época chuvosa, enquanto as temperaturas médias devem aumentar de modo mais significativo na estação seca. As informações geradas com esse estudo podem auxiliar na compreensão da variabilidade da precipitação no espaço e no tempo em Minas Gerais, bem como na previsão da ocorrência de episódios de seca severa e ondas de calor. Tais dados poderão ser utilizados em estudos de ecologia e para a modelagem da paisagem. Possíveis limitações para o uso de bases de dados globais e de GCMs para descrever fenômenos na escala de Minas Gerais são discutidas.

Palavras-chave: variabilidade climática, bases de dados globais, anomalias, cenários futuros.

---

* Comitê Orientador: Prof[a]. Dr[a]. Angela Maria Soares (Orientadora), Dr. Serge Rambal - DREAM/CEFE/CNRS (Co-orientador).

1 INTRODUCTION

In the *Summary of the Fourth Assessment Report*, the International Panel for Climatic Change (Solomon et al., 2007) concluded that the average global air temperature has increased during the twentieth century. A warming trend is forecasted for the next decades, altering the rainfall patterns in some areas of the globe (Rosenzweig et al., 2004; Slingo et al., 2005; Verdin et al., 2005; Lin 2007; Cerri et al., 2007). However, the projections of the impacts of global warming on regional weather are mostly uncertain due to the complex and site-specific interdependencies among landscape properties, environmental traits and policy decisions (Boulanger et al., 2006).

For these reasons, an accurate assessment of the state of the weather, in a fine space-time resolution, could be a suitable starting point to study ecological applications, at landscape level, related to weather variability. Studies with this scope could improve our knowledge about the effects of climate changes on the water budget, fire regime, land cover dynamics and on ecosystem functions and services. Ultimately, the comprehension of interactions of weather variability and landscape properties, at regional scale, could lead to improved resource management and better emergency planning to withstand the effects of extreme episodes on the ecosystems (Rosenzweig et al., 2004; Slingo et al., 2005; Lin 2007; Rodríguez-Lado et al., 2007; Silva et al., 2007).

There is a consensus that a variety of factors contribute to the climate variability across diverse regions of South America (Liebmann & Allured, 2005; Boulanger et al., 2005; Boulanger et al., 2006; Rocha et al.; 2006; Ferraz et al., 2006; Boulanger et al., 2007; Silva et al., 2007; Seth et al., 2007). The continent has unique geographical features, such as the sharp Andes Mountains, the world's largest rain forest in Amazonia, and deserts in Atacama and Altiplano. Additionally, the El Niño Southern Oscillation (ENSO) is reported to alter the rainfall pattern over the continent (Minuzzi et al., 2004; Ferraz et al., 2006;

Boulanger et al., 2006; Boulanger et al., 2007). In the Brazilian southeast, ENSO events are associated with more intense droughts and higher mean air temperatures in winter (Pereira et al., 2005; Prela et al., 2006). This concern has to do with three main characteristics of the region: energy production, which is generated by hydroeletric plants; agriculture, which is mostly dependent on rain to sustain production; and ecosystem conservation, which can become more vulnerable to drought and fire. In this context, there is a need for energy resource managers, scientists, agriculture administrators, policy makers and ecologists to better understand the intraseasonal-to-interannual variability of weather and its effects on the landscape properties.

With those considerations, the objective of this study was to characterize the structure of recent-past, present and future patterns of precipitation and temperature in Minas Gerais, southeast Brazil, via three different data sources: a global grid, a global circulation model and observed datasets from weather stations. The aim was to supply information about the use of datasets to the understanding, simulation and anticipation of the landscape's vulnerability to global changes in Minas Gerais.

2 MATERIAL AND METHODS

2.1 SITE CHARACTERISTICS

The State of Minas Gerais is located within the geographic limits of 14º-23º S and 40°-51ºW, with altitudes averaging from the maximum of 1200m and minimum of 150m (Figure 1). It is the largest in the Brazilian southeast region, with a surface area of 5.9×10^5 km^2, occupied by 20×10^6 inhabitants (Instituto Brasileiro de Geografia e Estatística, 2007). The predominant land use is for agricultural activities, especially corn (1.41×10^6 ha), eucalypt forests (1.20×10^6 ha), coffee (1.02×10^6 ha), milk production (6×10^{12} L.year^{-1}) and sugar cane (5.1×10^5 ha) (IBGE, 2007, Companhia Nacional de Abastecimento, 2007).

The predominant natural vegetation is the cerrado, a temperate savanna, which originally occupied 53% (3.0 x 10^5 km^2) of the area of the state (Bessa et al., 2002). The predominant climate type in Minas Gerais, according to Köppen's classification, is the Cwa (moist with mild dry winter and warm summer).

2.2 DATASETS

For the assessment of the space-time variability of mean temperature and precipitation in Minas Gerais, three sources of climatic data were used. One global dataset (CRU TS 2.1), a global circulation model (GCM) (CNRM-CM3); and weather station datasets (CPTEC-INPE and INMET). The CRU TS 2.1, from the Climate Research Unit (Mitchell & Jones, 2005), (http://www.cru.uea.ac.uk/timm/grid/CRU_TS_2_0.html) was composed of monthly observed temperature and precipitation values, extending from 1901 to 2002, covering the globe at a 0.5^o grid cell (Figure 1). The CNRM-CM3, from the Centre National de Recherches Météorologiques (Météo-France) (Salas-Mélia et al., 2005) is a coupled GCM, based on the ARPEGE-climate version 3. It comprises daily data in an aproximate 3° grid. Three periods were used: the recent-past climate from 1961 to 2000, and future scenarios in the 21st century: 2046-2065 and 2081-2100. The simulations for the future climate were made considering the IPCC A1B scenario (balanced across energy sources).

Data from the weather stations of the **I**nstituto **N**acional de **M**eteorologia (INMET) (http://www.inmet.gov.br/html/rede_obs.php) and from the **C**entro de **P**revisão do **T**empo e **E**studos **C**limáticos - **I**nstituto **N**acional de **P**esquisas **E**spaciais (CPTEC-INPE) (http://satelite.cptec.inpe.br/PCD/pcd.jsp?uf=12) were used to compose daily precipitation and mean temperature averages of three regions of Minas Gerais: south (3 weather stations – Lavras, Machado and Itajubá - from 1997 to 2006), north (2 weather stations – Janaúba and Salinas –

from 1918 to 2006) and west (2 weather stations – Araxá and Patrocínio – from 2000 to 2006).

2.3 ANOMALY CALCULATION AND DATA ANALYSIS

Monthly anomalies were calculated by subtracting the normal value from the observed value (1).

$$An = O_bV - N_mV \quad (1)$$

where: An is the monthly anomaly of mean temperature or precipitation, O_bV is the observed value and N_mV is the corresponding normal value from 1961-1990. The normal values were averages from 1961 to 1990, of each dataset. For the weather stations, the normal values were averaged from published data (Brasil, 1992) for each region: North (Montes Claros and Araçuaí); South (Machado and Lavras) and West (Araxá and Uberaba).

The analysis of anomalies was performed by plotting the monthly values of each year in box-plots representing the 10^{th}, 25^{th}, 75^{th} and 90^{th} percentile of the normal distribution. The high anomalies (ranging from the 75^{th} to the 90^{th} percentile) and low anomalies (ranging from the 10^{th} to the 25^{th} percentile) were used to fit regression equations. The parameters of the equations were considered significant by the *t*-test at $\alpha = 1\%$.

Spatial interpolation techniques were used to convert the discrete data into continuous data on Minas Gerais using the software Surfer (Surface Mapping System version 8.04, Golden Software Inc, Golden Colorado, USA). Experimental variograms were constructed and models were fitted by the least square method. The parameters of the variograms (variance, anisotropy, range, sill, slope and nugget) (Figure 2) were used in the construction of contour maps of average air temperature and precipitation.

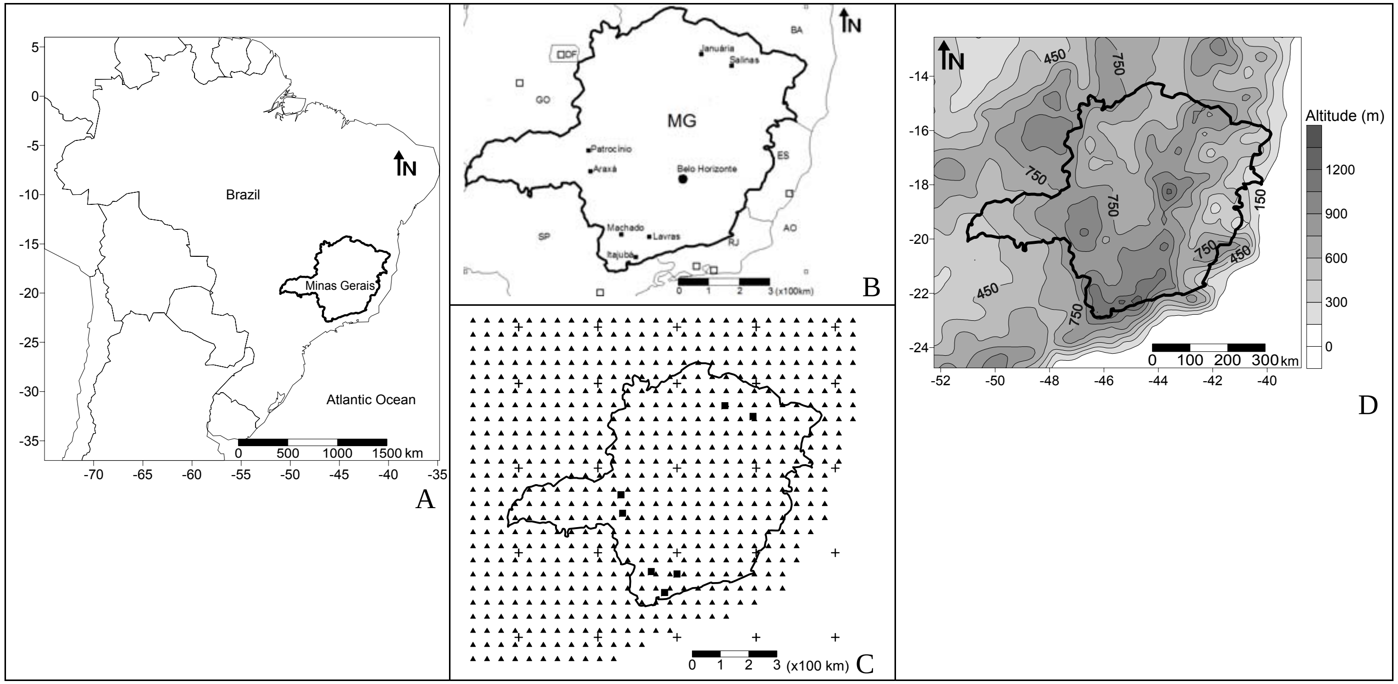

Figure 1 – (A) Location of Minas Gerais in the Brazilian southeast. (B) Location of the weather stations (■) and of the state's capital (●). Abbreviations indicate the neighbor states: SP – São Paulo, GO – Goiás, BA – Bahia, RJ – Rio de Janeiro, ES – Espírito Santo, DF – Distrito Federal. AO – Atlantic Ocean, MG – Minas Gerais. (C) An illustration of the grid points of the datasets used in the study: CRU TS 2.1 (▲); CNRM-CM3 (+); weather stations (■). (D) A representation of the topography of Minas Gerais through the altitude of the grid points of CRU TS 2.1 and CNRM-CM3 with the altitude of CPTEC and INMET weather stations.

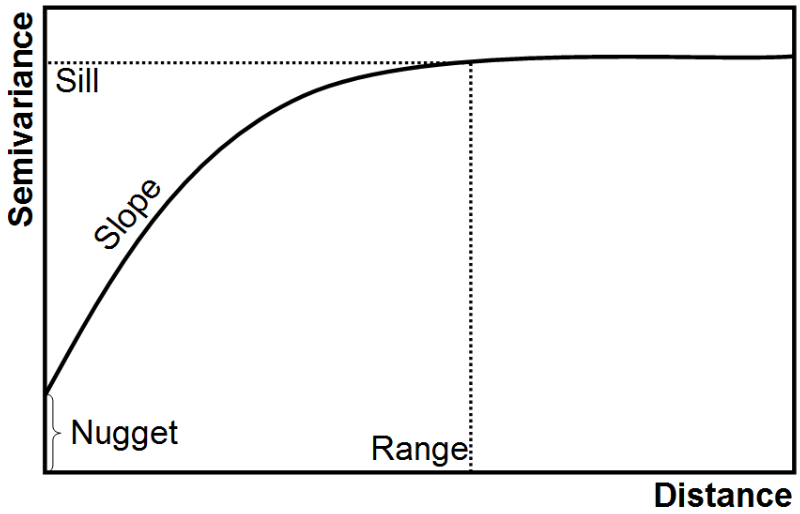

Figure 2 – A scheme of a theorical variogram (Adapted from Woodcock et al., 1988).

The CRU TS 2.1 dataset was divided in 3 time-series of 34 years (1901 to 1934, 1935 to 1968 and 1969 to 2002) and interpolated with the Kriging method (650 points over Minas Gerais). The Natural Neighbor interpolation method was used in the 25 points of the CNRM-CM3 dataset, in the three periods.

Time analyzes were made by standard variance analysis (ANOVA), considering the weather stations as replicates, or grid points as replicates (CRU TS 2.1 and CNRM-CM3) at a given time (month, year, season). The annual and seasonal anomalies observed in ENSO years were compared with anomalies of Non-ENSO years. The standard error was calculated and averages were compared by the Tukey test at $\alpha = 5\%$.

3 RESULTS

3.1 TEMPORAL VARIABILITY OF MEAN AIR TEMPERATURE AND PRECIPITATION IN MINAS GERAIS

The three datasets demonstrated the seasonal behavior of temperature and precipitation. In general, the period extending from December to March (wet season) was characterized by higher temperatures than the average values observed from May to August (dry season) ($P<0.05$). Also, the months of the wet season concentrated 85% of the annual precipitation. Moreover, the datasets also demonstrated the temporal variability caused by ENSO episodes in the precipitation and temperature of Minas Gerais. In general, the ENSO events marked smaller ($P<0.05$) annual and seasonal precipitation amounts and higher ($P<0.05$) mean temperature values in relation to periods without ENSO influence (Table 1).

The observed average ($\pm$ standard error) annual increment in the precipitation of 50 $\pm$ 88 mm accessed by the CRU TS 2.1 dataset along the last century was not significant (Figure 3A). The seasonal precipitation from CRU TS 2.1 was stable in 100 years: 221 $\pm$ 49 mm year^{-1} in the dry season and 1082 $\pm$ 110 mm year^{-1} in the wet season (Figure 3B). Whereas the average annual mean air temperature from the beginning of the 20th century (1901 to 1934) increased from 21.9 $\pm$ 0.3°C to 23.1 $\pm$ 0.4 °C at the end of that century (1969 to 2002) ($P<0.05$) (Figure 3C). The average seasonal mean temperatures were 23.1 $\pm$ 0.2 °C and 20.5 $\pm$ 0.3 °C for the wet and dry seasons, respectively, at the beginning of the 20th century. These values increased to 24.5 $\pm$ 0.5°C and 21.7 $\pm$ 0.4 °C, respectively, in the last 34 years of the dataset (Figure 3D).

The average annual precipitation from the GCM in the 1961 to 2000 period was 1681.7 $\pm$ 163 mm year^{-1} (Figure 4A). An increment in annual rainfall is forecasted in the future: 2046-2065 (1851 $\pm$ 190 mm year^{-1}) and 2085-2100 (1888 $\pm$ 160 mm year^{-1}). The average precipitation observed in the dry season was similar along the three periods studied (266 ± 55 mm $year^{-1}$) (Figure 4B). In the wet season, the averages observed were 1416 ± 148 mm $year^{-1}$ from 1961 to 2000. The future values are forecasted to increase ($P<0.05$): 1609 ± 156 mm $year^{-1}$ and 1618 ± 121 mm $year^{-1}$ for the periods from 2046 - 2065 and 2081 – 2100, respectively. The average annual mean air temperature was 21.6 ± 0.5°C to the period from 1961 to 2000 (Figure 4C). The values are predicted to rise to 23.8 ± 0.4°C ($P<0.05$) in 2046-2061, up to 24.8 ± 0.4°C ($P<0.05$) in the end of the 21st century. The average seasonal mean air temperature extracted from CNRM-CM3 were 22.8 ± 0.4 °C in the wet, and 20.5 ± 0.5 °C in dry season, for the period from 1961 to 2000 (Figure 4D).These values are predicted to increase ($P<0.05$), respectively, to 24.7 ± 0.4 °C and 23 ± 0.4 °C, in 2046-2065, with a new rise ($P<0.05$) to 25.6 ± 0.3 °C and 24 ± 0.5 °C, respectively in 2081-2100.

Table 1 – Average values ± standard error of precipitation and mean temperature observed in Minas Gerais in ENSO and Non-ENSO years.

		Precipitation (mm)		Temperature (C°)	
Dataset		ENSO	Non-ENSO	ENSO	Non-ENSO
CRU TS 2.1	Annual	1293.1±26.4	1364.8±9.6	22.5±0.1	22.1±0.1
	Wet	1053.8±24.7	1148.8±10.7	23.8±0.1	23.4±0.1
	Dry	239.3±8.0	216.1±4.8	21.2±0.1	20.8±0.1
Weather Stations (north of Minas Gerais)	Annual	618.1±73.0	986.3±48.4	24.5±0.2	23.8±0.1
	Wet	549.8±61.9	893.5±46.5	25.7±0.2	25.0±0.1
	Dry	68.2±13.4	92.7±9.2	23.3±0.2	22.5±0.1

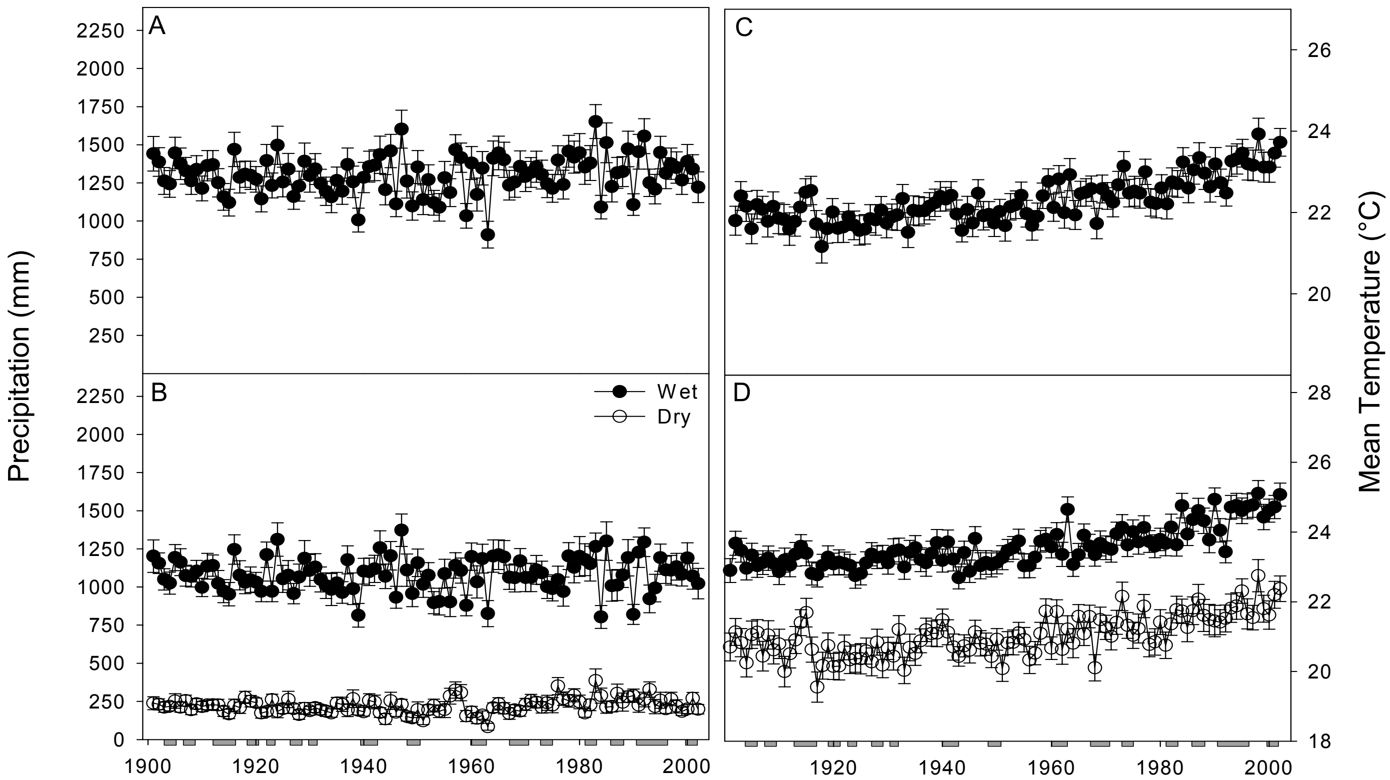

Figure 3 – Average annual (A) and seasonal (B) precipitation and average annual (C) and seasonal (D) mean air temperature in Minas Gerais from 1901 to 2002, according to CRU TS 2.1 dataset. Point and error bars represent, respectively, average ± standard error of 12 months (annual) and 6 months (seasonal). The bars on the x axis indicate the ENSO episodes during the observation period.

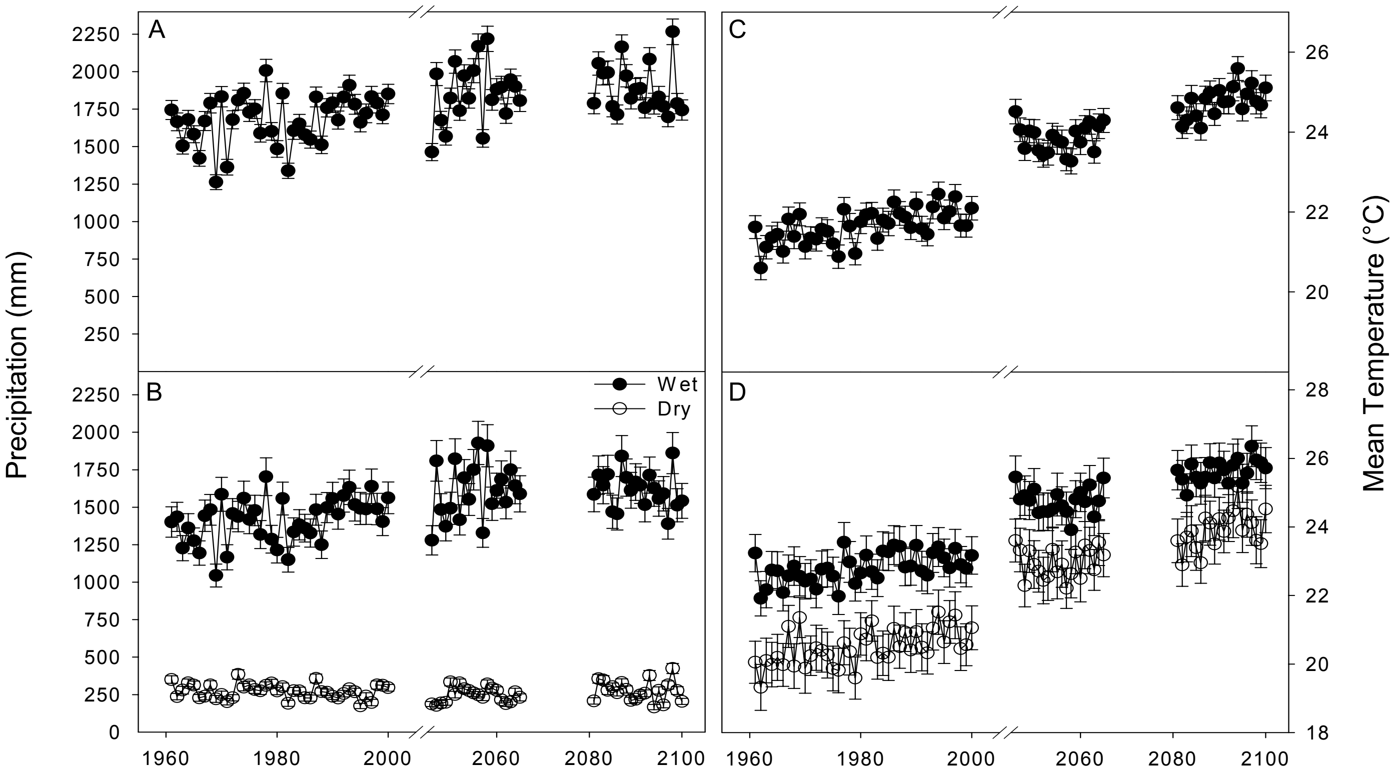

Figure 4 – Average annual (A) and seasonal (B) precipitation and average annual (C) and seasonal (D) mean air temperature in Minas Gerais from 1961 to 2000, from 2046 to 2065 and from 2081 to 2100 according to CNRM-CM3 dataset. Point and error bars represent, respectively, average ± standard error of 12 months (annual) and 6 months (seasonal).

The datasets from the weather stations of the north of Minas Gerais indicated a decrease ($P<0.05$) in the annual precipitation from 1918 to 1947 (934 $\pm$ 46 mm $year^{-1}$) to the beginning of the 2000's (1977 to 2006 – 836 $\pm$ 52 mm $year^{-1}$) (Figure 5A). The precipitation values of the wet season decreased ($P<0.05$) from 857 $\pm$ 52 mm $year^{-1}$ to 712 $\pm$ 51 mm $year^{-1}$ (Figure 5B). However the precipitation of the dry season remained similar along the period (110 $\pm$ 42 mm $year^{-1}$). The increment in the annual temperature observed comparing the first 30 years (24.2 $\pm$ 0.4 ^oC) with the last 30 years (25.0 $\pm$ 0.3 ^oC) was not significant (Figure 5C), whereas the mean temperature increased in the wet season, from 29.5 $\pm$ 0.3 ^oC to 32.3 $\pm$ 0.2 ^oC (Figure 5D). The values observed in the dry season were similar, ranging from 22.8 $\pm$ 0.5 ^oC to 23.9 $\pm$ 0.3 ^oC.

The annual precipitation increased from 2000 to 2006 in the south (from 999 $\pm$ 36 mm $year^{-1}$ to 1503 $\pm$ 52 mm $year^{-1}$) (Figure 6A) and west (from 1208 $\pm$ 91 mm $year^{-1}$ to 1618 $\pm$ 62 mm $year^{-1}$) (Figure 7A) of Minas Gerais. The seasonal precipitation values also increased in both seasons ($P<0.05$) (Figures 6B and 7B). However, the annual and seasonal mean temperature were similar ($P>0.05$) in the south (20.5 $\pm$ 0.8^oC) (Figure 6C) and in the west (21.3 $\pm$ 0.7^oC) (Figure 7C), with exception of 2004, which was the warmest year in the west region, also showing the lowest precipitation values in the wet season.

3.2 TEMPORAL DISTRIBUTION OF ANOMALIES

The annual precipitation anomalies, from CRU TS 2.1, ranged between -137 and 175 mm $month^{-1}$ in the last century, with no increments in the average values (Figure 8A), whereas the average temperature anomalies indicated an increment ($P<0.05$) of 1.1 $\pm$ 0.2 °C from 1901 to 2002 (Figure 8B). In general, seasonal anomalies of temperature did not differ ($P>0.05$) (Figures 8D, F). The anomalies observed in the wet season ranged between -1.3 ^oC and 1.7 ^oC and anomalies of the dry season between -1.7 ^oC and 1.4 ^oC.

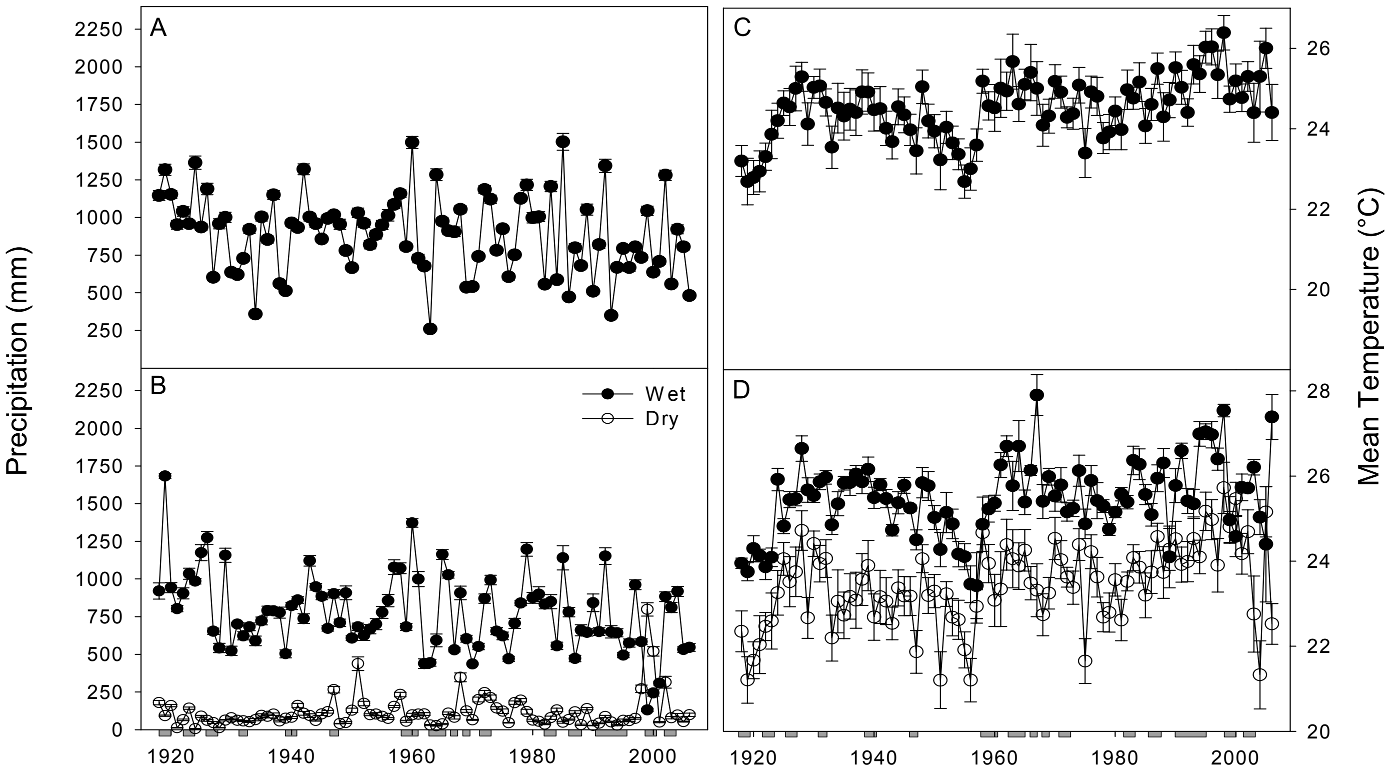

Figure 5 – Average annual (A) and seasonal (B) precipitation and average annual (C) and seasonal (D) mean air temperature in the north of Minas Gerais from 1918 to 2006 according to the Januária and Salinas weather stations dataset. Point and error bars represent, respectively, average ± standard error of 12 months (annual) and 6 months (seasonal). The bars on the x axis indicate the ENSO episodes during the observation period.

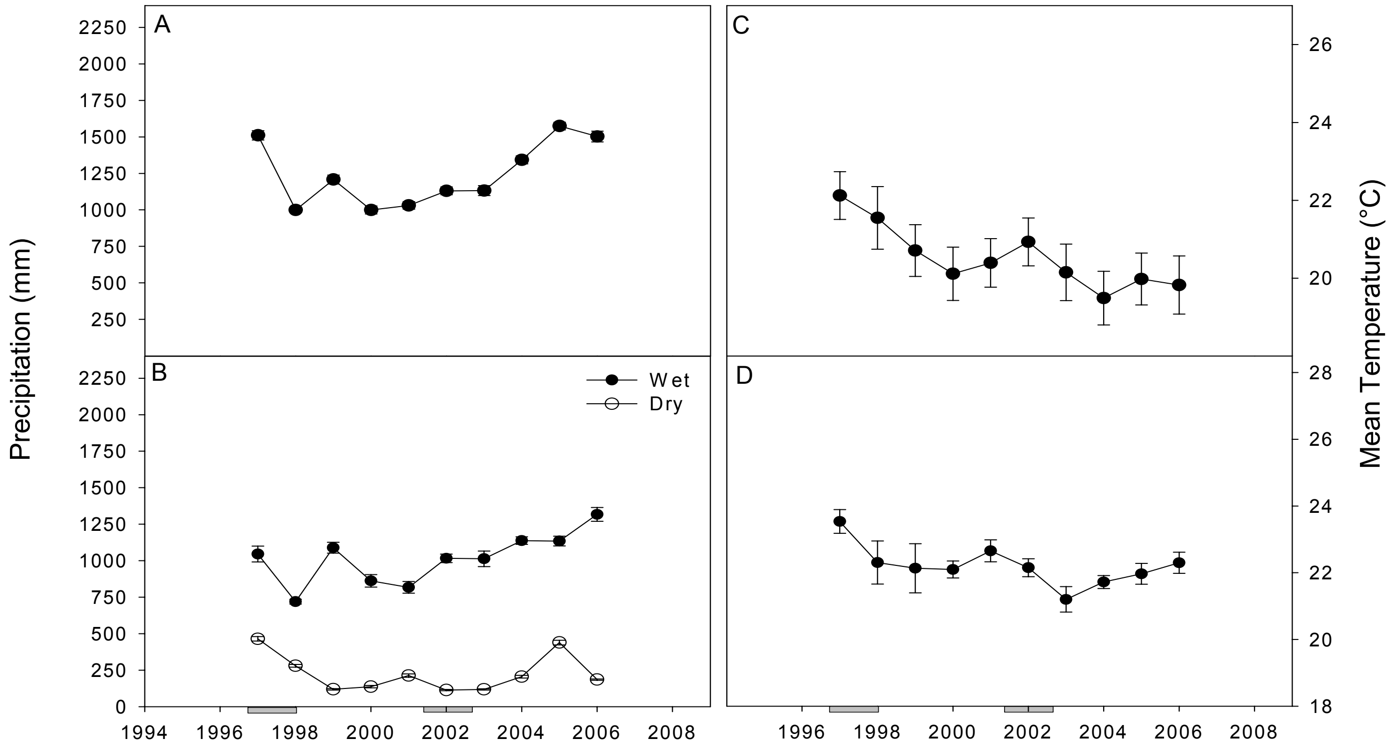

Figure 6 – Average annual (A) and seasonal (B) precipitation and average annual (C) and seasonal (D) mean air temperature in the in the south of Minas Gerais from 1997 to 2006 according to the Lavras, Itajubá and Machado weather stations dataset. Point and error bars represent, respectively, average $\pm$ standard error of 12 months (annual) and 6 months (seasonal). The bars on the x axis indicate the ENSO episodes during the observation period.

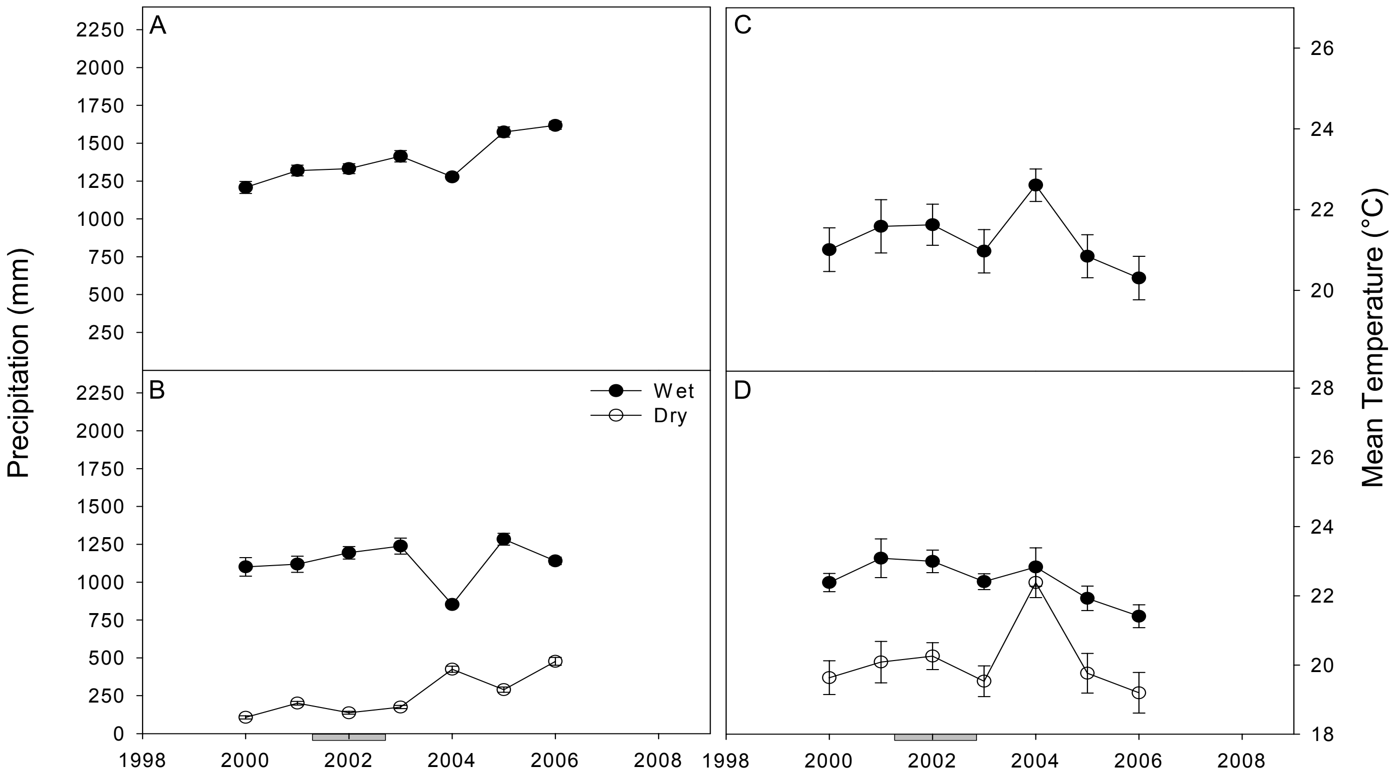

Figure 7 – Average annual (A) and seasonal (B) precipitation and average annual (C) and seasonal (D) mean air temperature in the in the west of Minas Gerais from 2000 to 2006 according to Patrocínio and Araxá weather stations dataset. Point and error bars represent, respectively, average ± standard error of 12 months (annual) and 6 months (seasonal). The bars on the x axis indicate the ENSO episodes during the observation period.

The average anomalies in annual precipitation observed from 1961 to 2000, according to CNRM-CM3, were between -28 to 33 mm $month^{-1}$ (Figure 9A). This interval is predicted to range between -12 and 54 mm $month^{-1}$ and from 7 to 55 mm $month^{-1}$ in 2046-2065 and 2081-2100, respectively. These increments were significant ($P<0.05$) among the three analyzed periods. The annual anomalies, observed for mean temperature, also showed an increase of 2.2 $\pm$ 0.4 °C and 3.1 $\pm$ 0.4 °C in the periods from 2046 - 2065 and 2081 – 2100, respectively ($P<0.05$) (Figure 9B). The seasonal temperature anomalies were higher in the dry than wet season ($P<0.05$) (Figures 9D, F). The estimation of increment to the middle of the 21st century (2041 to 2065) is of 1.9 $\pm$ 0.2 °C in the wet, and 2.5 $\pm$ 0.3 °C in dry season. From the middle to the end of the century (2051 to 2100), the seasonal anomalies are forecasted to be similar: 0.9 $\pm$ 0.3 °C in the wet, and 1.0 $\pm$ 0.2 °C in dry season.

Seasonal anomalies of precipitation were smaller and more constant in time in the dry season than wet season for CNRM-CM3 and CRU TS 2.1 datasets (Figures 8 C, E and 9 C, E). The precipitation anomalies from CRU TS 2.1 tended to decrease from 1901 to 2002 while high anomalies tended to increase. The CNRM-CM3 predicted an increment in seasonal precipitation anomalies in the two seasons. The increment is forecasted to be higher ($P<0.05$) in the wet season (209 $\pm$ 30 mm $year^{-1}$) than in the dry season (5 $\pm$ 23 mm $year^{-1}$) at the end of the 21st century.

Average annual anomalies in the north of Minas Gerais ranged between -75.5 and 190.5 mm $years^{-1}$ and -1.1 and 2.5 °C for precipitation and mean air temperature, respectively (Figures 10A, B). The average anomalous precipitation were lower in the wet season than in the dry season (-77 $\pm$ 24 mm $years^{-1}$ and -4 $\pm$ 48 mm $years^{-1}$) (Figures 10 C, E), but the temperature anomalies were similar among seasons (average of 0.9 $\pm$ 0.4 °C) (Figures 10 D, F).

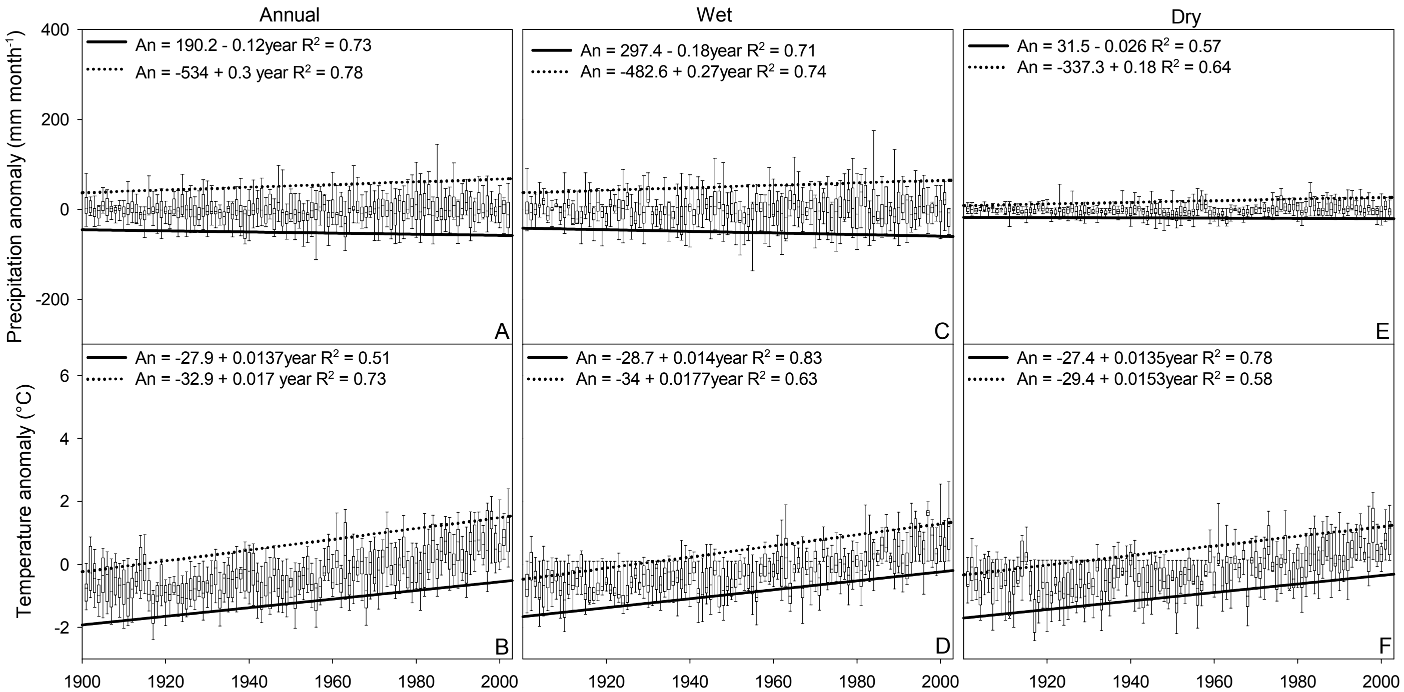

Figure 8 – Annual (A) and seasonal (C-wet and E-dry) precipitation anomalies and annual (B) and seasonal (D-wet and F-dry) anomalies of mean temperature calculated from CRU TS 2.1 dataset over Minas Gerais from 1901 to 2002. The thin solid lines in the box plots indicate the median of the raw data. The top and bottom of the boxes indicate the 25th and the 75th percentiles, the whiskers above and below the boxes indicate the 90th and 10th percentiles. The solid and the dotted linear regressions indicate, respectively, the occurrence of high and low anomalies.

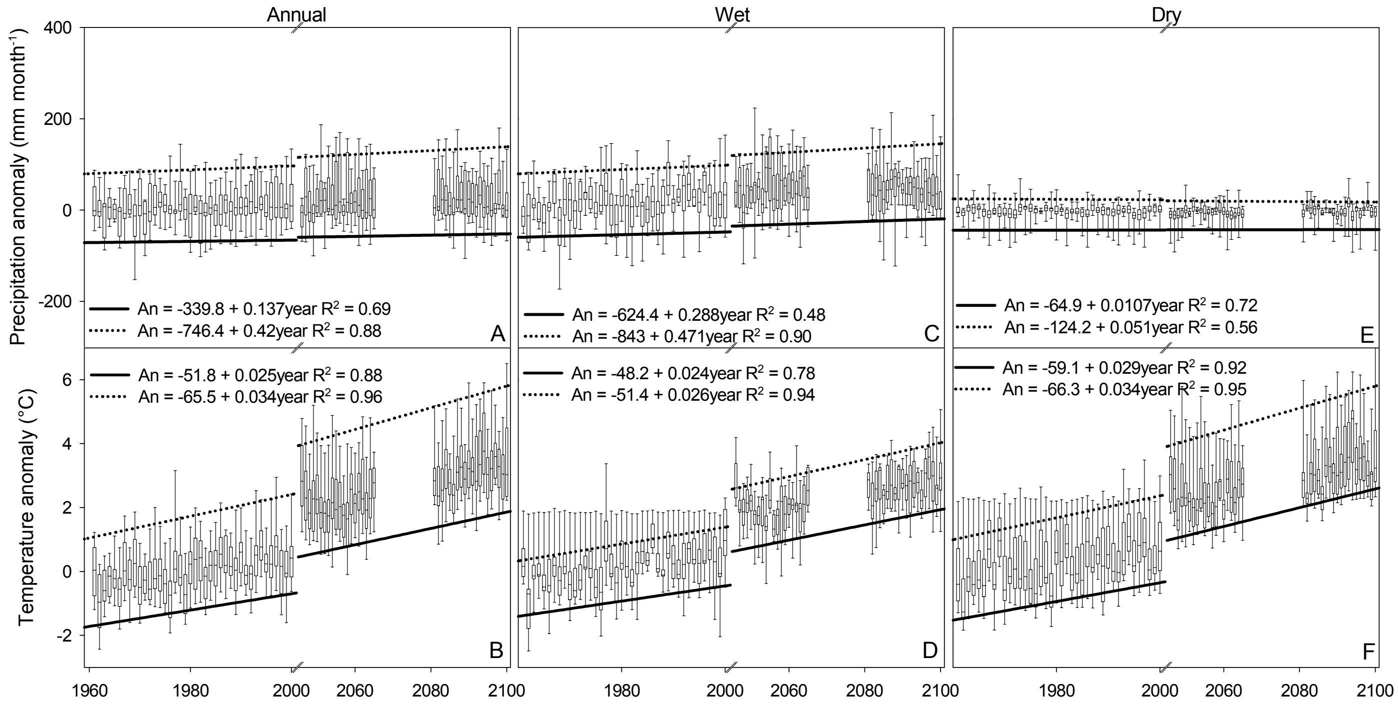

Figure 9 – Annual (A) and seasonal (C-wet and E-dry) precipitation anomalies and annual (B) and seasonal (D-wet and F-dry) anomalies of mean temperature calculated from CNRM-CM3 dataset over Minas Gerais from 1961 to 2000, from 2046 to 2065 and from 2081 to 2100. The thin solid lines in the box plots indicate the median of the raw data. The top and bottom of the boxes indicate the 25th and the 75th percentiles, the whiskers above and below the boxes indicate the 90th and 10th percentiles. The solid and the dotted linear regressions indicate, respectively, the occurrence of high and low anomalies.

In general the data from the south and west of Minas Gerais revealed the beginning of the year 2000 as a period with lower precipitation than normal. In the south, the temperature increment was followed by a reduction in annual and seasonal precipitation ($P<0.05$). The average anomalies for annual precipitation and mean temperature ranged between -42.0 and -46.8 mm year^{-1} and 3.3 and 0.6 ^{o}C (Figures 11A, B). The values of the wet season ranged between -15.2 and -145.3 mm year^{-1} and 2.5 and 0.2 ^{o}C (Figures 11 C, D) and the dry season values ranged from -28.0 and 30.4 mm year^{-1} and 1.4 and 4.7 ^{o}C (Figures 11 E, F). In the west the annual anomalies ranged between -31.2 and -3.0 mm year^{-1} and -1.1 and 1.2 ^{o}C (Figures 12 A, B). Anomalies in mean air temperature for wet and dry seasons ranged between -0.8 and 0.4^{o}C and -0.3 and 2.6 ^{o}C, respectively (Figures 12D, F). For precipitation the values ranged between -74.2 and 36.5 mm year^{-1} and -26.5 and 25.2 mm year^{-1} respectively (Figures 12C, E).

For precipitation, the ENSO episodes did not showed significant effects in the annual or seasonal CRU TS 2.1 anomalies. In the north of Minas Gerais, we observed that ENSO events reduced the annual precipitation with no effects over the seasonal rainfall amounts (Figures 13A, C). In general, annual and seasonal anomalies of mean air temperature were higher in periods with ENSO episodes for the CRU TS 2.1 and for the weather stations datasets ($P<0.05$) (Figures 13B, D).

3.3 SPATIAL STRUCTURE OF PRECIPITATION AND MEAN AIR TEMPERATURE IN MINAS GERAIS

In general, the values of precipitation tended to increase and the temperatures tended to decrease with the altitude (Figures 9 A, B). Also, the temperatures tended to increase with the latitudes (Figure 9D), and to be higher at longitudes varying from -44^{o} to -46^{o} (Figure 9F). The correlation of precipitation with the latitude and longitude was less clear and not significant ($P>0.01$).

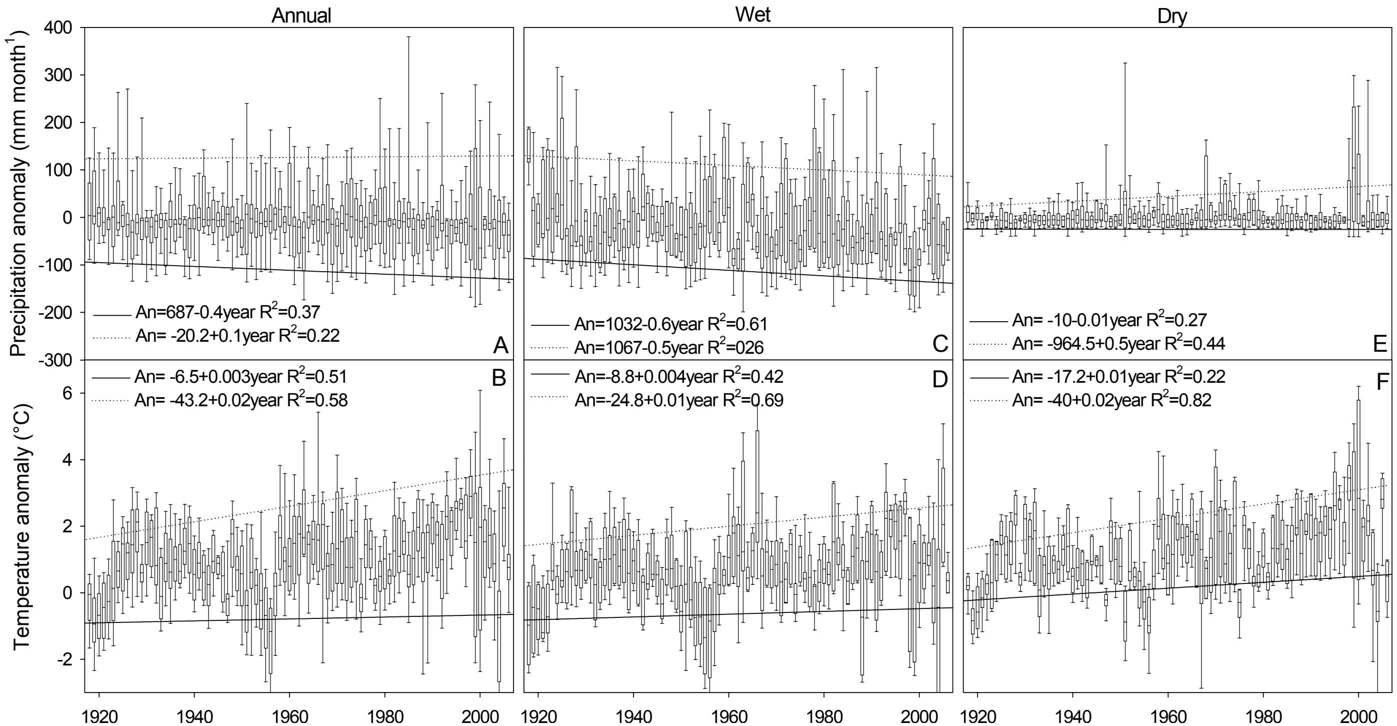

Figure 10 – Annual (A) and seasonal (C-wet and E-dry) precipitation anomalies and annual (B) and seasonal (D-wet and F-dry) anomalies of mean temperature calculated from Januária and Salinas weather stations datasets over the north of Minas Gerais from 1918 to 2006. The thin solid lines in the box plots indicate the median of the raw data. The top and bottom of the boxes indicate the 25th and the 75th percentiles, the whiskers above and below the boxes indicate the 90th and 10th percentiles. The solid and the dotted linear regressions indicate, respectively, the occurrence of high and low anomalies.

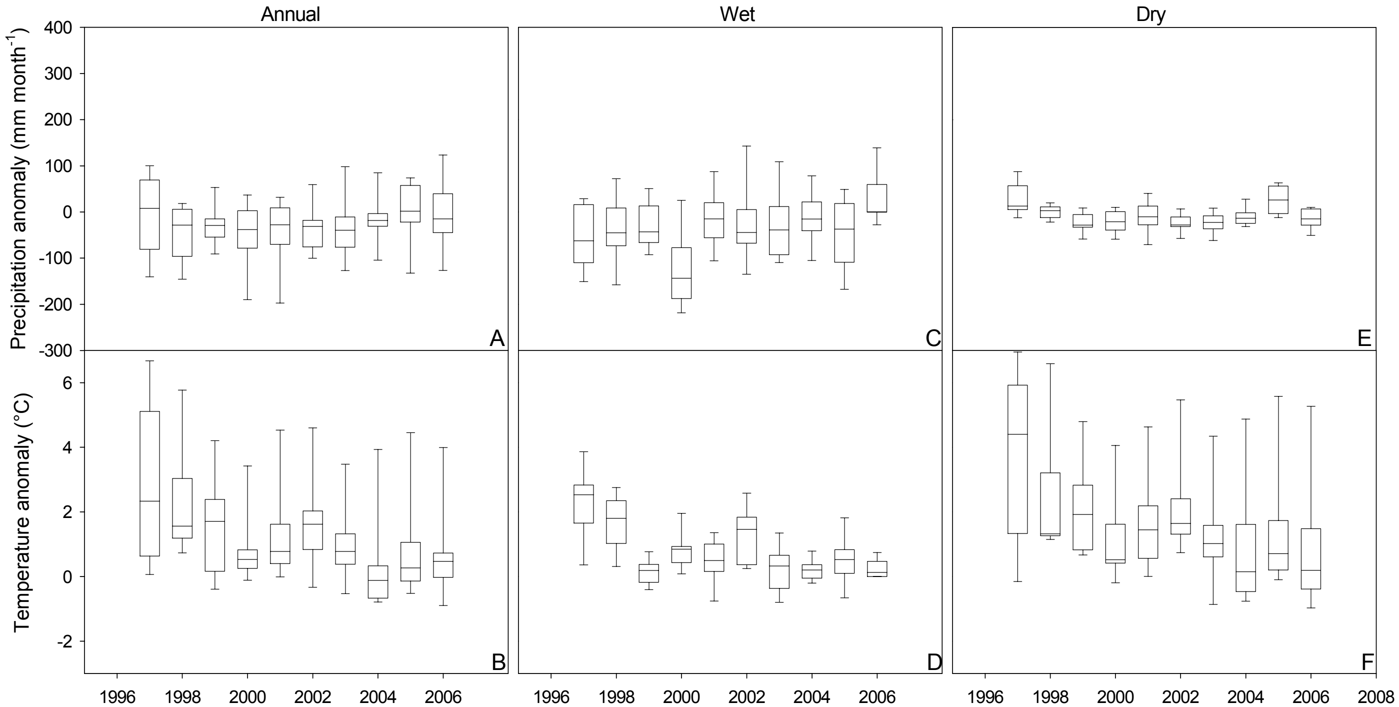

Figure 11 – Annual (A) and seasonal (C-wet and E-dry) precipitation anomalies and annual (B) and seasonal (D-wet and F-dry) anomalies of mean temperature calculated from Lavras, Itajubá and Machado weather stations datasets over the south of Minas Gerais from 1997 to 2006. The thin solid lines in the box plots indicate the median of the raw data. The top and bottom of the boxes indicate the 25th and the 75th percentiles, the whiskers above and below the boxes indicate the 90th and 10th percentiles.

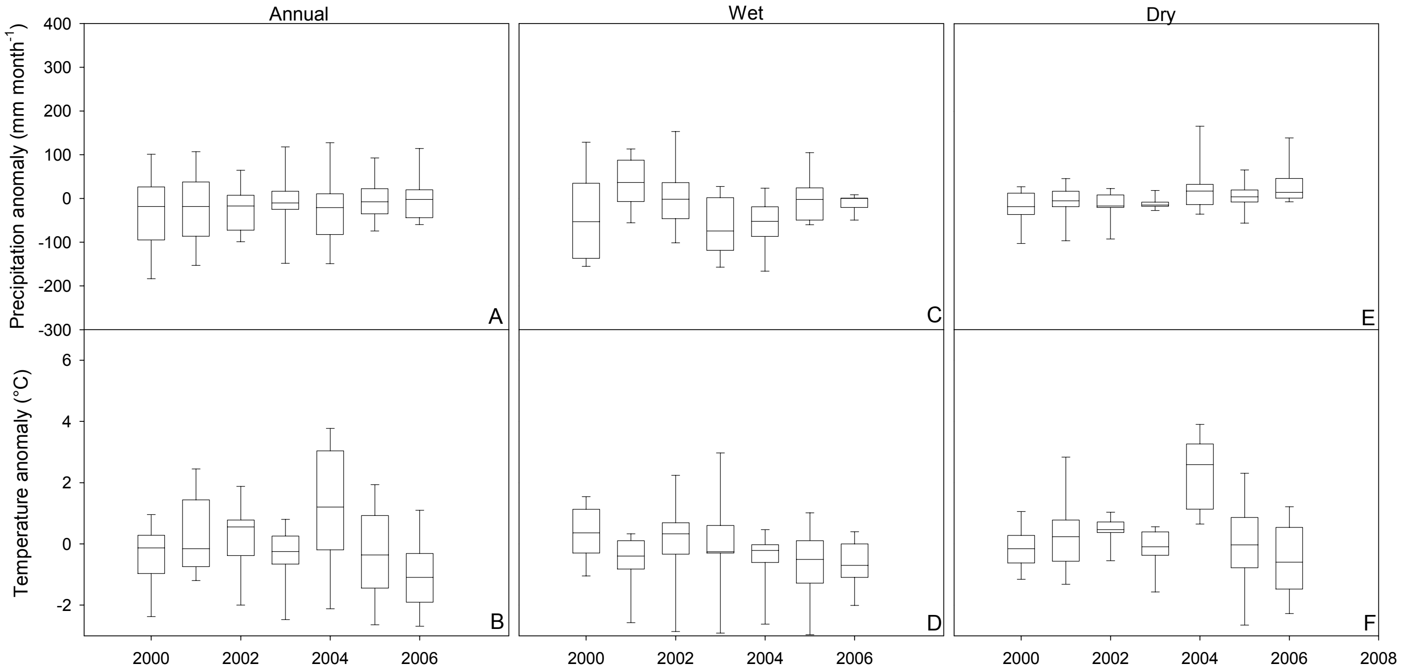

Figure 12 – Annual (A) and seasonal (C-wet and E-dry) precipitation anomalies and annual (B) and seasonal (D-wet and F-dry) anomalies of mean temperature calculated from Araxá and Patrocínio weather stations datasets over the west of Minas Gerais from 1918 to 2006. The thin solid lines in the box plots indicate the median of the raw data. The top and bottom of the boxes indicate the 25th and the 75th percentiles, the whiskers above and below the boxes indicate the 90th and 10th percentiles.

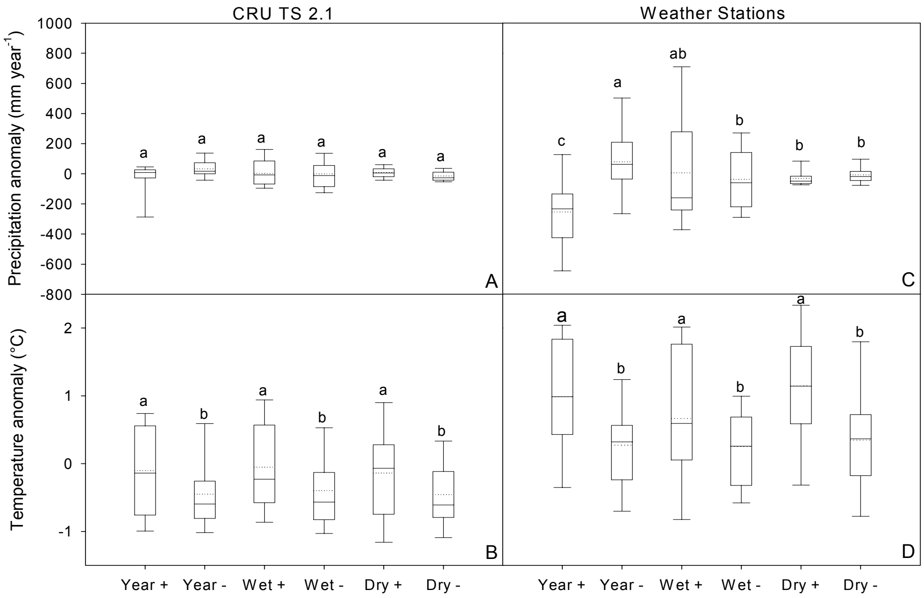

Figure 13 – Annual and seasonal anomalies of precipitation (A and C) and mean air temperature (B and D) distributed in year with ENSO (+) and in years with No ENSO (-) episodes in the climatic datasets (CRU TS 2.1 – A, B and Weather Stations - C, D). The solid line and the dotted line in the box plots indicate, respectively, the median and the average of the raw data. The top and bottom of the boxes indicate the 25th and the 75th percentiles, the whiskers above and below the boxes indicate the 90th and 10th percentiles. Categories that do not share the same letter, in the horizontal sense, are significantly different at P<0.05.

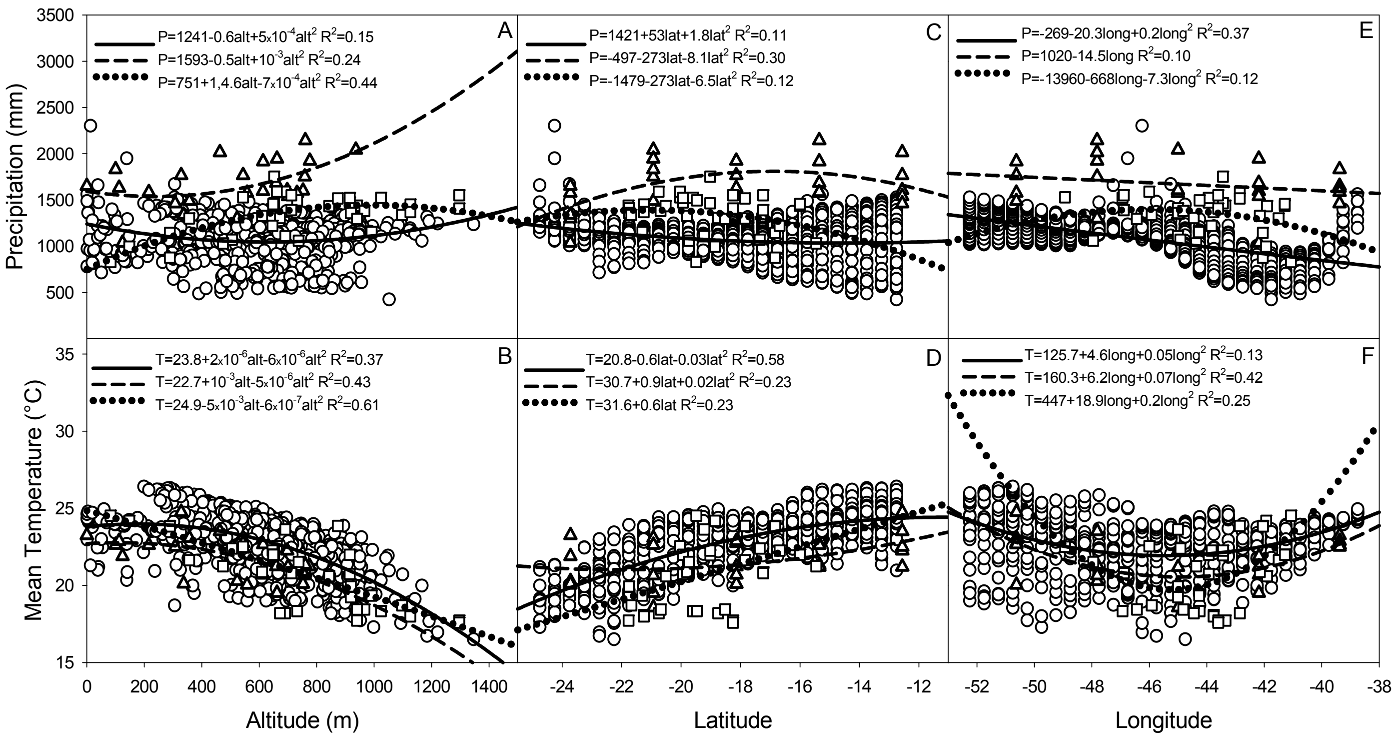

Figure 14 – Spatial distribution of precipitation (A, C and E) and mean air temperature (B, D and F) in relation to the altitude, latitude and longitude in Minas Gerais. The values correspond to averages to each grid point from CRU TS 2.1 dataset (1901-2002) (O —), from CNRM-CM3 dataset (1961-2000) (Δ ---) and from normal values (1961-1990) from weather stations in Minas Gerais, according to Brasil (1992) (□ ·····).

The spatial structure of mean temperature and precipitation, based on the gridded datasets, was examined by experimental variograms. In general, the spatial variability of the weather variables, at annual and seasonal scales, was almost identical in all directions, meaning that the phenomenon is isotropic in time. However, the shapes of the variograms indicated spatial dependency of precipitation and temperature, according to the regression model adjusted to each experimental variogram, indicating that the phenomenon is anisotropic in space. The variograms of the calculated anomalies were similar to the variograms of the climatic variables in the same periods. The variograms of CRU TS 2.1 dataset stabilized at approximately 12^o. Nuggets ranged between 7000 and 10000 (mm year^{-1})^2 for precipitation and 0.0 and 0.8 (^{o}C)^2 for temperature. For the CNRM-CM3 dataset, there were no nuggets in the models adjusted for precipitation, however the values range between 0.2 and 0.5 (^{o}C)^2 for temperature. Variograms stabilized at approximately 8^o.

The standard error of the spatial structure of CRU TS 2.1 dataset ranged between 270.5 and 317 mm year^{-1} for precipitation and from 1.8 to 2.2 ^{o}C for mean air temperature. In the wet season, the standard error for precipitation ranged between 276.3 and 300 mm year^{-1} and for temperature the values were 1.5 ^{o}C in all period. The spatial standard error in the dry season for mean air temperature ranged between 2.1 and 2.5 ^{o}C, and between 148.1 to 177 mm year^{-1} for precipitation. The values of anisotropy for precipitation ranged between 95.2 and 150.8^o and for temperature from 31.6 to 70^o. For CNRM-CM3 dataset, the spatial standard errors for temperature were of 1.4 ^{o}C per year, 1.3 ^{o}C in the wet and 1.7 ^{o}C in the dry seasons. Values for precipitation ranged between 246.7 and 288.5 mm year^{-1}, 313.8 and 333 mm year^{-1} and 130.4 and 167.5 mm year^{-1} for annual, wet and dry seasons, respectively.

For anomalies, calculated from these datasets, the standard errors ranged from 0.3 to 0.5 ^{o}C for mean temperature in annual, as well as seasonal scale. The standard errors for precipitation anomalies in the space ranged between 34.7 and 42.3 mm $year^{-1}$ in the dry, 127 and 138.7 mm $year^{-1}$ in the wet seasons and from 132.6 to 137 mm $year^{-1}$ on an annual scale. The anisotropy values for precipitation ranged between 83.7 and 160.1°, 76.8 and 130.5° and 48.8 and 90.4° in the year, wet and dry seasons, respectively. For temperature these values were between 23.2 and 58°, 30.2 and 53.4° and 59.3 and 87.5°, respectively.

The maps generated from the interpolation of the CNRM-CM3 dataset showed similarities with the maps of CRU TS 2.1 dataset. In general, we observed that the annual precipitation and mean temperature increased in the whole Minas Gerais throughout the 20th century. The southeast region of the state had a higher precipitation level and low mean air temperature than the north and the west regions, forming a precipitation gradient that decreased from the south to the north. The temperature gradient increased in the same pattern (Figure 15).

We used the CNRM-CM3 dataset to show the seasonal behavior observed from 1961 to 2000 over the state of Minas Gerais (Figure 16) and future patterns of anomalies (Figures 17 and 18). The gradient of temperature and precipitation, from the southeast to northwest of Minas Gerais, was observed in the annual and in the wet season (Figures 16A, B, D, E). In the dry season, the center-south of the state showed the lowest temperatures, the rest of Minas Gerais showed a similar pattern of temperature (Figure 16C). The precipitation was similar in the whole area of Minas Gerais in this season (Figure 16F).

The spatial patterns of anomalies in future scenarios confirmed the modification of values and patterns of precipitation and temperature over Minas Gerais, observed in the temporal analysis (Figures 17 and 18). The maps indicated a reduction of precipitation in the state in the dry season (ranging between 0 and -100 mm) (Figures 17C, F) and an increase in the wet season (ranging between 100 and 500 mm) (Figures 17B, E), resulting in an increase in the annual rainfall (Figures 17A, D). The mean air temperature is predicted to increase more in the dry season (ranging between 2 and 4^{o}C) (Figures 18C, F) than in the wet season (ranging between 2 and 3^{o}C) (Figures 18B and 17E). In general, the precipitation anomalies are predicted to increase from south to north whereas the temperature is predicted to increase from east to west.

Table 2 compares the annual and seasonal average values of mean air temperature and precipitation from weather stations dataset, considering the period from 2000 to 2006 in the south, west and north of Minas Gerais. The south was colder than the other two regions ($P<0.05$). The north of Minas Gerais was the warmest region and the west showed intermediate temperature values. The precipitation in the dry season was similar ($P>0.05$) in the three regions. The north region showed lower ($P<0.05$) average values of annual and summer precipitation than the south and west. The values observed in the annual and in the wet season in the south and west of Minas Gerais were similar.

Table 2 – Annual and seasonal average values of precipitation and mean air temperatures observed from 2000 to 2006 by weather stations of the north, south and west of Minas Gerais, Brazil.

	North	South	West
		Precipitation (mm)	
Annual	917±74	1244.7±92	1354.4±51
Wet	737±56	1042±69	1131.6±61
Dry	180±29	202.1±45	222.7±47
		Mean temperature (^{o}C)	
Annual	23.3±0.1	20.1±0.2	21.4±0.3
Wet	24.8±0.1	22.0±0.2	22.6±0.2
Dry	21.8±0.2	15.6±0.2	20.2±0.4

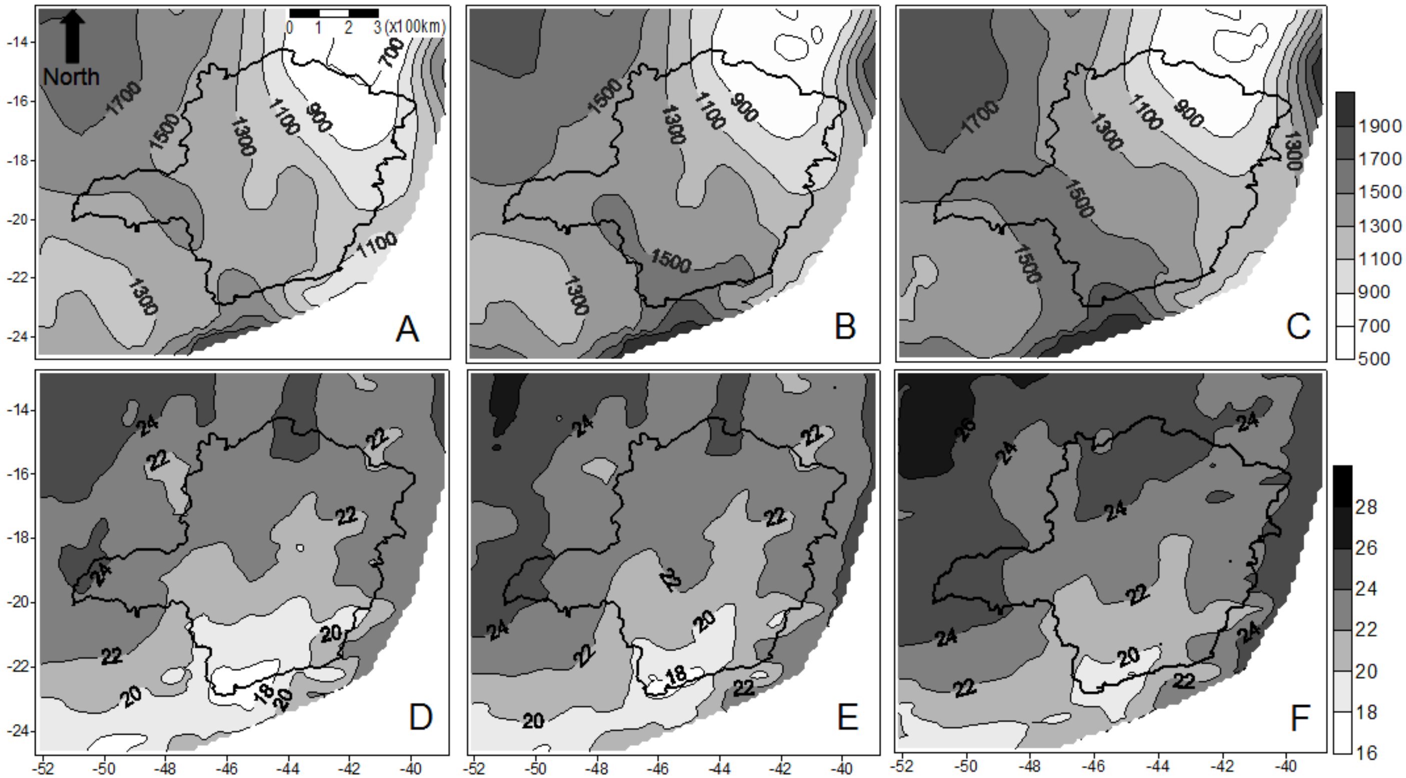

Figure 15 – Maps of annual precipitation (mm) and mean air temperature (°C) according to the CRU TS 2.1 dataset. A – precipitation from 1901-1934; B – precipitation from 1935-1968; C – precipitation from 1969 – 2002; D – temperature from 1901-1934; E –temperature from 1935-1968; F –temperature from 1969 – 2002.

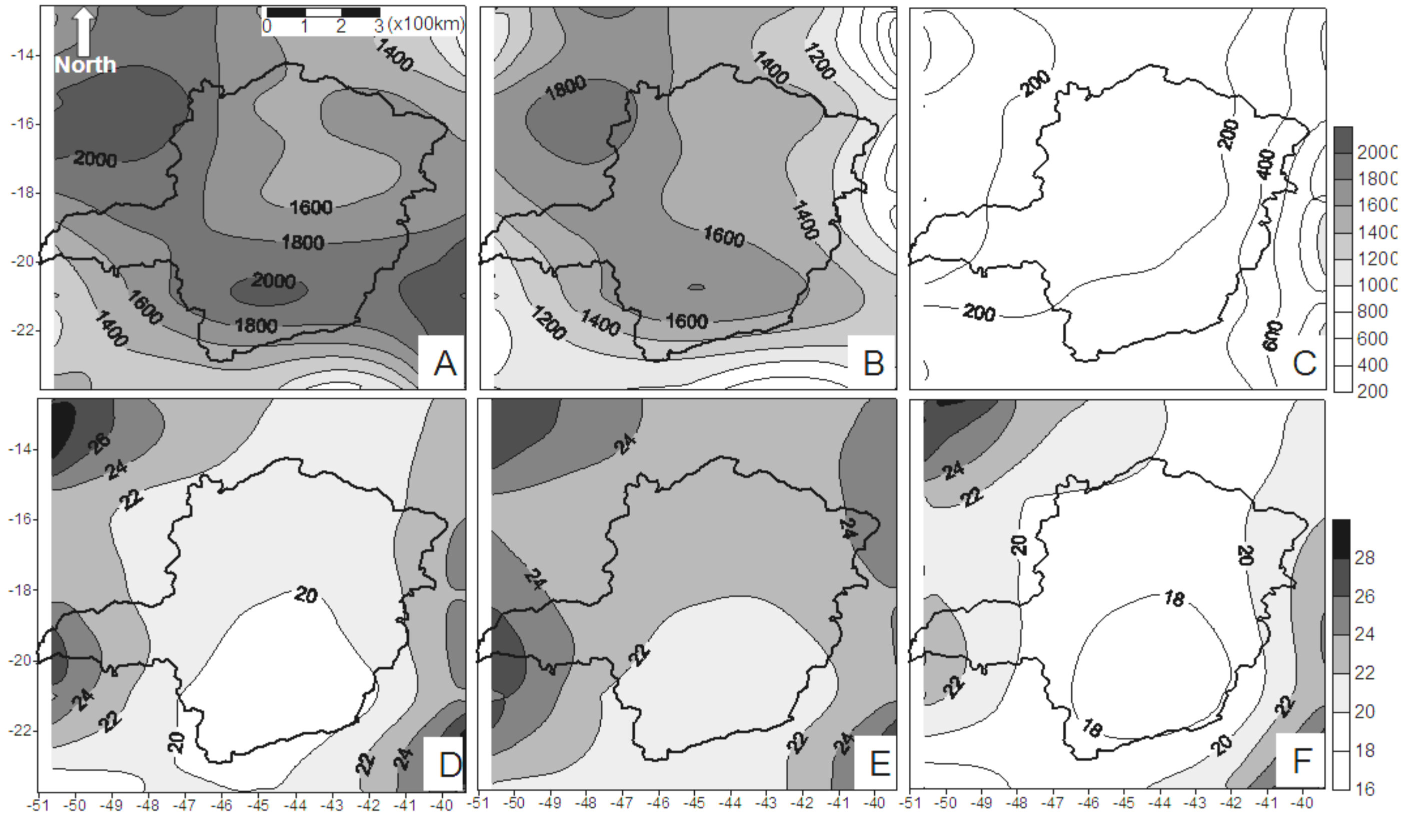

Figure 16 – Maps of precipitation (mm) and mean air temperature (°C) according to the CNRM-CM3 dataset over the period from 1961 to 2000. A – annual precipitation; B – precipitation of the wet season; C – precipitation of the dry season; D – annual temperature; E –temperature of the wet season; F –temperature of the dry season.

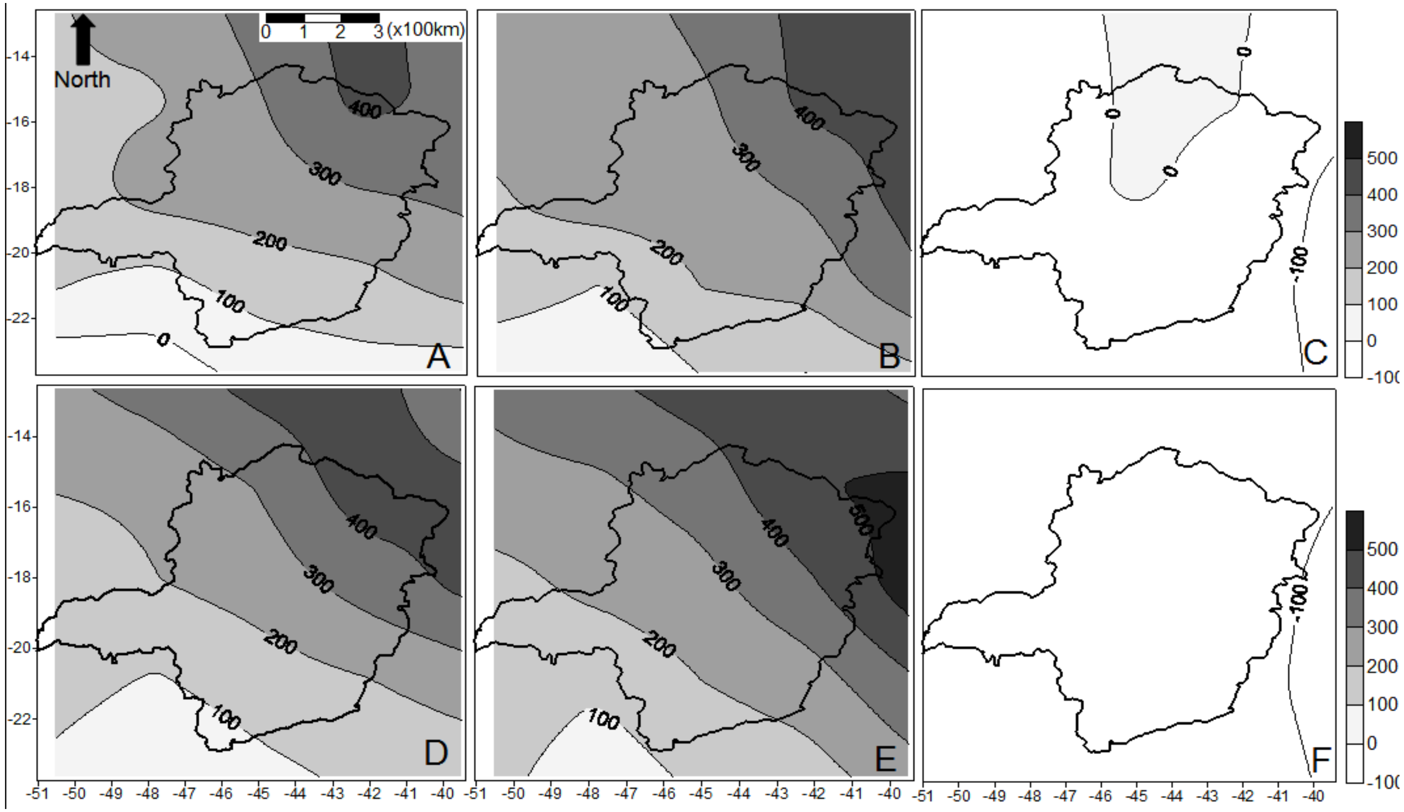

Figure 17 – Maps of precipitation anomalies (mm) from CNRM-CM3. A – annual from 2046-2065; B – wet season from 2046-2065; C – dry season from 2046-2065; D –annual from 2081 to 2100; E – wet season from 2081 to 2100; F – dry season from 2081 to 2100.

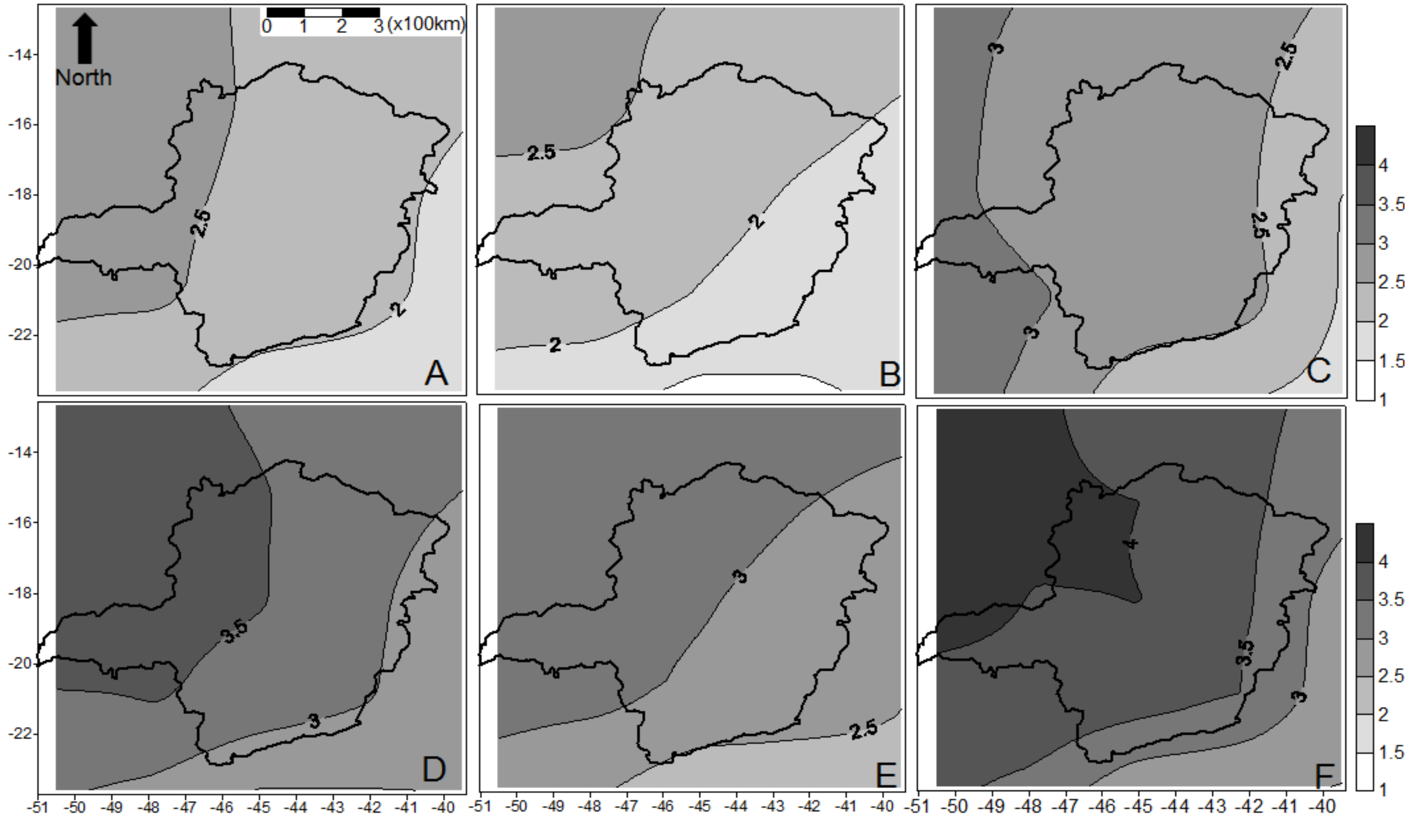

Figure 18 – Maps of temperature anomalies (^oC) from CNRM-CM3. A – annual from 2046-2065; B – wet season from 2046-2065; C – dry season from 2046-2065; D –annual from 2081 to 2100; E – wet season from 2081 to 2100; F – dry season from 2081 to 2100.

4 DISCUSSION

The datasets used in the depiction of the variability of mean temperature and precipitation in Minas Gerais showed similarities of patterns and values in space and time. Our results were compatible with observations made elsewhere, concerning the values of seasonal-to-annual percentage of rainfall, and the effects of ENSO episodes on the weather variability (Valeriano & Picini, 2000; Silva et al., 2007; Rodrigués-Lado et al., 2007). Considering the anomalies simulated by the three datasets, the ENSO cycle had pronounced effects on air temperature, which tended to reach higher values in the dry season of the years with ENSO episode. Precipitation deficits were also observed in northern Minas Gerais during ENSO years. In our studies, a considerable event-to-event variability was observed, especially in the magnitude of anomalies at the beginning of ENSO episodes. Those observations are consistent with previous studies on El Niño impacts in this region of South America (Minuzzi et al., 2004; Boulanger et al., 2005).

Although the datasets demonstrated the tendency of increment in the annual values of air temperature and precipitation with time, we could observe that the temperatures of the dry season increased more than in the wet season, decreasing the amplitudes between seasonal values. Another generalized tendency was that precipitation tended to increase more in the wet season, concentrating in December, January and February, remaining almost constant, at low values, in the dry season. If these temporal and spatial tendencies could be confirmed, the dry season would be warmer and drier, and the wet season would be warmer and wetter in the near-future. The result of those trends could be the increment of the frequency of severe drought in the dry season, affecting the landscape properties, with potential impacts over the land cover, fire regime and ecosystem functioning.

Nonetheless, the potential impacts are yet unpredictable, since they depend on feedback responses of the biosphere-atmosphere system and political decisions. Also, it is important to notice that the predictions reported in this study by the CNRM-CM3 dataset refer to just one future scenario (A1B) of greenhouse gas emissions and radiative forcing, and the results can be somewhat modified by considering other scenarios of energy use, political decisions and feedback responses of the biosphere-atmosphere system. Pielke Junior et al. (2008) relate that the scenarios used by the IPCC's fourth assessment report underestimated the scale of the technological challenge associated with stabilizing greenhouse-gas concentrations. Within this consideration, the assumptions made with this exercise may be optimistic.

On the other hand, it is necessary to consider that while numerous studies have focused on climatic change scenarios and their interrelation with the landscape for mid-latitudes, relatively few have examined tropical regions. The ones with this focus emphasized seasonal large-scale climate predictions (Wang et al., 2004; Sun et al., 2005, 2006; Boulanger et al., 2006, 2007). However, the predictions of climatic changes and their impacts in tropical regions are as important as in mid-latitudes because of their characteristics related to economic activity based on agriculture and the role of natural ecosystems in the carbon sequestration and water budget, which could have an effect of reducing the impacts of global changes over the climatic system of those regions (Boulanger et al., 2005; Stiviari et al., 2005; Cerri et al., 2007).

Therefore, the assessment of the landscape vulnerability to global changes is dependent on a regional depiction of the weather variability, and characterization of weather in space. Since data on vegetation cover is frequently provided by remote sensing, the use of gridded climatic datasets is of interest. Boulanger et al. (2005, 2006), among others, also used CRU TS 2.1 and CNRM-CM3 datasets to describe the climate over the South American continent and verified that, at least for precipitation, the comparison with satellite-based rainfall was relatively good, supplying an approach able to simulate regional patterns of weather in a realistic manner.

A major problem concerning the use of global climatic grids to assess the regional climatic patterns is related to the scale at which simulations can be considered skillful (Grotch & MacCracken 1991; Biau et al., 1999; Giorgi, 2001). For instance, one of the largest uncertainties in global climate datasets concerns the small-scale of hydrological processes, such as precipitation, infiltration, or evaporation. Nonetheless, such processes are important in the determination of vegetation responses to climatic changes. The lack of regional details in the global datasets is due to the resolutions at which they are integrated. In this study, we observed that on a regional scale within Minas Gerais, precipitation and air temperature can be influenced by topography, different land use or proximity to the sea. These patterns have been also observed by similar studies (Liebmann & Allured, 2005; Dufresne et al., 2006; Douville et al., 2006; Seth et al., 2007).

The variographical analysis gave good results in the determination of the meanings of downscaling global datasets to the relatively small scale structure under study. Other studies, within the scope of characterization of spatial structure of the precipitation and temperature in Minas Gerais, obtained similar results (Silva & Clarke, 2004; Camargo et al., 2005; Rodrigués-Lado et al., 2007). We also observed that global grids showed a similar pattern of spatial dependence of precipitation and temperature, without any time dependence in the spatial distribution of the phenomenon. The spatial dependence is probably linked to the discrimination in weather characteristics among the regions of the state, as discussed before. The values of spatial anisotropy revealed a covariance structure (values tend to be more similar in one or more preferred directions than in others) that is usually related to patterns in the orientation of the phenomenon, as discussed by Biau et al. (1999).

Because global datasets exhibit substantial uncertainties on regional climate, as discussed before, there is much potential for regional climatic models. Meanwhile it has been suggested that regional models generated from statistics of observational data may be excellent tools for examining weather variability and climate change (Huntingford & Gash 2005; Seth et al., 2007). A suitable method to model weather on the scale of Minas Gerais would be the use of observational data associated with geographical information to compose a temperature and precipitation regression analysis. Some studies of this kind were conducted in São Paulo state (Valeriano & Picini, 2000; Rodrigués-Lado et al., 2007), resulting in models able to predict air temperature with great accuracy and spatial distribution, using only latitude and altitude as independent variables. This kind of model would be interesting for ecological studies and landscape modeling (Almeida & Landsberg, 2003; Seth et al., 2007; Rodrígues-Lado et al., 2007; Boulanger et al., 2005, 2006, 2007).

Although currently there are weather stations covering most of Minas Gerais territory, historical climatic information is seriously impeded by a series of obstacles: a lack of adequate observational data; a few scattered observations, some of which may be missing at any given time and which are unlikely to reflect actual or recent-past weather variability; timeliness of station reports and high-cost data. These problems have limited the use of data from weather stations, and are probably limiting the development of regional climatic models in Minas Gerais.

Nonetheless, until these problems can be solved and more data from weather stations can be accessible to scientists, the use of global grids and GCMs could be good alternatives for the development of regional landscape models and applications in ecophysiological studies. Nowadays this is of interest since information about climatic structure in time and space is needed to improve the understanding of the influence of weather variability on vegetation functioning and ecosystem dynamics, and to develop suitable methods to use this information to set up mitigation strategies. In this context, actually the use of global datasets and models may provide a reliable and economic means of obtaining extensive spatial climatic data to supply ecological needs.

5 REFERENCES

ALMEIDA, A. C.; LANDSBERG, J. J. Evaluating methods of estimating global radiation and vapor pressure deficit using a dense network of automatic weather stations in coastal Brazil. **Agricultural and Forest Meteorology**, Amsterdam, v. 18, n. 3-4, p. 237-250, Sept. 2003.

BESSA, K. C. F. O.; BORGES, G. V.; SOARES, B. R. Dinâmica sócio-econômica das "cidades locais"situadas em áreas de cerrado mineiro. **Caminhos de Geografia**, Uberlândia, v. 3, n. 5, p. 9-29, Sept. 2002.

BRASIL. Ministério da Agricultura e Reforma Agrária. Secretaria Nacional de Irrigação. Departamento Nacional de Meteorologia. **Normais Climatológicas:** 1961-1990. Brasília, 1992. 84 p.

BIAU, G. Estimation of precipitation by Kriging in the EOF space of the sea level pressure field**. Journal of Climate**, Boston, v. 12, n. 4, p. 1070-1085, Apr. 1999.

BOULANGER, J. P.; LELOUP, J.; PENALBA, O.; RUSTICUCCI, M.; LAFON, F.; VARGAS, W. Observed precipitation in the Paraná-Plata hydrological basin: long-term trends, extreme conditions and ENSO teleconnections. **Climate Dynamics**, New York, v. 24, n. 4, p. 393-413, Mar. 2005.

BOULANGER, J. P.; MARTINEZ, F.; SEGURA, E. C. Projection of future climate change conditions using IPCC simulations, neural networks and Bayesian statistics. Part 1: Temperature mean state and seasonal cycle in South America. **Climate Dynamics**, New York, v. 27, n. 3-4, p. 233-259, Aug. 2006.

BOULANGER, J. P.; MARTINEZ, F.; SEGURA, E. C. Projection of future climate change conditions using IPCC simulations, neural networks and Bayesian statistics. Part 2: Precipitation mean state and seasonal cycle in South America**. Climate Dynamics**, New York, v. 28, . 2-3, p. 255-271, Feb. 2007.

CAMARGO, M. B. P. de; BRUNINI, O.; PEDRO JÚNIOR, M. J. P.; BARDIN, L. Variabilidade espacial e temporal de dados termopluviométricos diários da rede de estações agrometeorológicas do Instituto Agronômico (IAC). **Bragantia**, Campinas, v. 64, n. 3, p. 473-483, jul./set. 2005.

CERRI, C. E. P.; SPAROVEK, G.; BERNOUX, M.; EASTERLING, W. E.; MELILLO, J. M.; CERRI, C. C. Tropical agriculture and global warming: impacts and mitigation options. **Scientia Agricola**, Piracicaba, v. 64, n. 1, p. 83-99, jan./fev. 2007.

COMPANHIA NACIONAL DE ABASTECIMENTO. **Segundo levantamento da safra de café 2007/2008.** 2007. Disponível em: <http://www.conab.gov.br/conabweb/download/safra/3BoletimCafe.pdf>. Acesso em: 31 out. 2007.

DOUVILLE, H.; SALAS-MÉLIA, D.; TYTECA, S. On the tropical origin of uncertainties in the global land precipitation response to global warming. **Climate Dynamics**, New York, v. 26, n. 4, p. 367-385, Mar. 2006.

DUFRESNE, J. L.; SALAS-MÉLIA, D; DENVIL, S.; TYTECA, S.; ARZEL, O; BONY, S.; BRACONNOT, P.; BROCKMANN, P.; CADULE, P.; CAUBEL, A.; CHAUVIN, F.; DÉQUÉ, M.; DOUVILLE, H.; FAIRHEAD, L.; FICHEFET, T.; FOUJOULS, M. A.; FRIEDLINGSTEIN, P.; GRANDPEIX, J. Y.; GUÉRÉMY, J. F.; HOURDIN, F.; IDELKADI, A.; KRINNER, G.; LEVY, C.; MADEC, G.; MARQUET, P.; MARTI, O.; MUSAT, I.; PLANTON, S.; ROYER, J.F.; SWINGEDOUW, D.; VOLDOIRE, A. Simulation du climat récent et futur par les modèles du CNRM et de l'IPSL. **La Météorologie**, Paris, v. 55, p. 45-59, 2006.

FERRAZ, S. E. T.; AMBRIZZI, T.; ROCHA, R. P. da; CUANDRA, S. V. Precipitation and temperature variability over south America from 1860 to 2100. In: INTERNATIONAL CONFERENCE ON SOUTHERN HEMISPHERE METEOROLOGY AND OCEANOGRAPHY, 8., 2006, Foz do Iguaçu. **Proceedings…** Foz do Iguaçu: INPE, 2006. p. 1527-1534.

GIORGI, F. Modelling regional climate change. **Science and Development Network.** 2001. Available at: <http://www.scidev.net/dossiers/index.cfm?fuseaction=printarticle&dossier=4&policy=30>. Access in: Sept. 24 2007.

GROTCH, S.; MacCRACKEN, M. The use of general circulation models to predict regional climate change. **Journal of Climate**, Boston, v. 4, n. 3, p. 286–303, Mar. 1991.

HUNTINGFORD, C.; GASH, J. Climate equity for all. **Science**, Washington, v. 309, n. 5742, p. 1789, 2005.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. **Censo populacional e agropecuário 2007**. 2007. Disponível em: <http://censos2007.ibge.gov.br/>. Acesso em: 02 fev. 2008.

LIEBMANN, B.; ALLURED, D. Daily precipitation grids for South America. **Bulletin of the Amerian Meteorological Society**, Boston, v. 86, n. 11, p. 1567-1570, Nov. 2005.

LIN, B. B. Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. **Agricultural and Forest Meteorology,** Amsterdam, v. 144, n. 1-2, p. 85–94, May 2007.

MINUZZI, R. B.; SEDIYAMA, G. C.; COSTA, J. M. N. da; RIBEIRO, A. Influência do fenômeno La Niña nos veranicos do Estado de Minas Gerais. **Revista Brasileira de Agrometeorologia**, Jaboticabal, v. 12, n. 3, p. 341-348, 2004.

MITCHELL, T. D.; JONES, P. D. An improved method of constructuing a database of monthly climate observations and associated high-resolution grids. **International Journal of Climatology**, Sussex, v. 25, n. 6, p. 693-712, May 2005.

PEREIRA, C. S.; ESPÍRITO SANTO, C. M. do; GIAROLLA, E. An in situ-based climatology of the sea surface temperature field for the southwestern Atlantic Ocean and its anomalies in enso years. **Revista Brasileira de Meteorologia**, Jaboticabal, v. 20, n. 3, p. 333-346, 2005.

PIELKE JUNIOR, R.; WIGLEY, T.; GREEN, C. Dangerous assumptions. **Nature**, London, v. 452, n. 7187, p. 531-532, 2008.

PRELA, A.; GARCIA, B. I. L.; PEREIRA, A. R. Variação de graus-dia em Piracicaba (SP), em anos de El Niño e La Niña. **Bragantia**, Campinas, v. 65, n. 3, p. 527-532, jul./set. 2006.

ROCHA, R. P. da; AMBRIZZI, T.; CUADRA, S. V.; FERRAZ, S. E. T.; FERNANDES, J. P. R. REGCM3 simulations nested in the Hadley center model over South America: the present day climate. In: INTERNATIONAL CONFERENCE ON SOUTHERN HEMISPHERE METEOROLOGY AND OCEANOGRAPHY, 8., 2006, Foz de Iguaçu. **Proceedings…** Foz do Iguaçu: INPE, 2006. p. 373-378.

RODRÍGUES-LADO, L.; SPAROVEK, G.; VIDAL-TORRADO, P.; DOURADO NETO, D.; MACÍAS-VÁZQUEZ, F. Modelling air temperature for the state of São Paulo, Brazil. **Scientia Agricicola**, Piracicaba, v. 64, n. 5, p. 460-467, set./out. 2007.

ROSENZWEIG, C.; STRZEPEK, K.M.; MAJOR, D.C.; IGLESIAS, A.; YATES, D.N.; McCLUSKEY, A.; HILLEL, D. Water resources for agriculture in a changing climate: international case studies. **Global Environmental Change**, Oxford, v. 14, n. 4, p. 345–360, Dec. 2004.

SALAS-MÉLIA, D.; CHAUVIN, F.; DÉQUÉ, M.; DOUVILLE, H.; GUÉRÉMY, J. F.; MARQUET, P.; PLANTON, S.; ROYER, J. F.; TYTECA, S. Description and validation of the CNRM-CM3 global coupled model. **Climate Dynamics,** New York, 2005.

SETH, A.; RAUCHER, S. A.; CAMARGO, S. J.; QIAN, J. H.; PAL. J. S. RegCM3 regional climatologies for South America using reanalysis and ECHAM global model driving fields. **Climate Dynamics**, New York, v. 28, n. 5, p. 461-480, Apr. 2007.

SILVA, B. C. da; CLARKE, R. T. Análise estatística de chuvas intensas na bacia do rio São Francisco. **Revista Brasileira de Meteorologia**, Jaboticabal, v. 19, n. 2, p. 265-272, 2004.

SILVA, V. B. S.; KOUSKY, V. E.; SHI, W.; HIGGINS, W. An improved gridded historical precipitation analysis for Brazil. **Journal of Hydrometeorology**, Boston, v. 8, n. 4, p. 847-861, Aug. 2007.

SLINGO, J. M.; CHALLINOR, A. J.; HOSKINS, B. J.; WHEELER, T. R. Introduction: food crops in a changing climate. **Philosophical Transactions of the Royal Society**, London, v. 360, n. 1463, p. 1983–1989, Nov. 2005.

SOLOMON, S.; QIN, D.; MANNING, M.; MARQUIS, M.; AVERYT, K.; TIGNOR, M. M. B.; MILLER JUNIOR, H. L.; CHEN, Z**.** (Ed. Working Group I) **Climate Change 2007**: the physical science basis: summary for policymakers. Paris: IPCC**,** 2007. (Fourth Assessment Report).

STIVIARI, S.; M. S.; OLIVEIRA, A. P. de; SOARES, J. On the climate impact of the local circulation in the Itaipu lake area. **Climatic Change**, Dordrecht, v. 72, n. 1-2, p. 103–121, Sept. 2005.

SUN, L. H.; MONCUNILL, D. F.; LI, H.; MOURA, A. D.; FILHO, F. A. S. Climate downscaling over Nordeste, Brazil, using the NCEP RSM97. **Journal Climate,** Boston**,** v. 18, n. 4, p. 551–567, Feb. 2005.

SUN, L.; MONCUNILL, D. F.; LI, H.; MOURA, A. D.; DE ASSIS, F.; ZEBIAK, S. E. An operational dynamical downscaling prediction system from Nordeste Brazil and the 2002–04 real-time forecast evaluation. **Journal of Climate,** Boston, v. 19, n. 10, p. 1990–2007, May 2006.

VALERIANO, M. de M.; PICINI, A. G. Uso des de informação geográfica para a geração de mapas de médias mensais de temperatura do Estado de São Paulo. **Revista Brasileira de Agrometeorologia**, Santa Maria, v. 8, n. 2, p. 255-262, jul./dez. 2000.

VERDIN, J.; FUNK, C.; SENAY, G.; CHOULARTON, R. Climate science and famine early warning. **Philosophical Transactions of the Royal Society**, London, v. 360, n. 1463, p. 2155–2168, Nov. 2005.

WANG, A. Q.; TENHUNENA, J.; DINHA, N. Q.; REICHSTEINA, M.; VESALAB, T.; KERONEN, P. Similarities in ground- and satellite-based NDVI time series and their relationship to physiological activity of a Scots pine forest in Finland. **Remote Sensing of Environment**, Amsterdam, v. 93, n. 1-2, p. 225–237, Oct. 2004.

WOODCOCK, C. E.; STRAHLER, A. H.; JUPP, D. L.. The use of variograms in remote sensing. I. Scene models and simulated images. **Remote Sensing of Environment**, v. 25, n. 3, p. 323-348, Aug. 1988.

CHAPTER III

Land cover structure and fire regime in Minas Gerais: an approach to the assessment of landscape vulnerability to global changes

ABSTRACT

BARBOSA, João Paulo Rodrigues Alves Delfino. Land cover structure and fire regime in Minas Gerais: an approach to the assessment of landscape vulnerability to global changes. In:______. **Vulnerability of the Minas Gerais landscape to global changes:** an initial step to a bottom-up approach. 2008. Chap. 3, 193 p. Thesis (Agronomy/Plant Physiology) – Federal University of Lavras, Lavras. *

The lack of organized attempts to measure impacts of land cover structure and fire occurrence on water and carbon fluxes is a threat to the current knowledge on landscape functioning. The objective of this work was the analysis of regional patterns of land cover structure and fire occurrence in Minas Gerais, southeast Brazil, to provide information for the assessment of the landscape vulnerability to global changes. The analysis of land cover structure was carried out over vegetation maps of three regions (north, south and west) at different times, and under high and low anthropogenic pressure, using a set of metrics derived from fractal analysis. The fire regime was studied by the Normalized Fire Index (NFI), distributed in a 0.5^o grid, from 1997 to 2006, through three different remote sensing products of fire detection (ASTR, TRMM, NOAA). A fourth dataset, extending from 1981 to 2000, was used to study the influence of ENSO events on fire occurrence. Regression equations were generated from temperature and precipitation anomalies of three weather datasets: (CRU TS 2.1, CNRM-CM3 and weather stations) with NFI anomalies to verify the climatic risk of fire occurrence in Minas Gerais over the next decades. The results demonstrated that most of the cerrado vegetation in the north and west of Minas Gerais has been replaced by croplands. The cerrado patches were larger and more abundant in the past and in the zones under low anthropogenic pressure. The dynamics of the landscape processes may be modified by agriculture, which was identified as the major factor influencing the land cover pattern in the three study sites. Fire was most frequent in these agricultural areas, and was closely correlated to weather variability and El Niño occurrence. More than 90% of the annual fire occurred in the dry season. The higher fire frequency was detected in the north, in the zones under high anthropogenic pressure, in the borders of cerrado with croplands/pasture. Based on temperature and precipitation anomalies, we could observe that the risk of fire occurence tends to increase in Minas Gerais in the next decades.

Key-words: fire frequency, landscape fragmentation, weather anomalies, landscape dynamics.

---

* Guidance Committee: Prof. Dr. Angela Maria Soares (Adviser), Dr. Serge Rambal - CEFE/CNRS (Co-adviser).

RESUMO

BARBOSA, João Paulo Rodrigues Alves Delfino. Estrutura da cobertura do solo e regime de queimadas em Minas Gerais: uma abordagem para o estudo da vulnerabilidade da paisagem às mudanças globais. In:______. **Vulnerabilidade da paisagem de Minas Gerais às mudanças globais:** um passo inicial para uma abordagem tipo *bottom-up*. 2008. Cap. 3, 193 p. Tese (Agronomia / Fisiologia Vegetal) – Universidade Federal de Lavras, Lavras.*

A ausência de estudos que visem quantificar os impactos da cobertura do solo e da ocorrência de queimadas, nos fluxos de água e de carbono, tem prejudicado o conhecimento do funcionamento da paisagem. Esse estudo objetivou avaliar os padrões de cobertura do solo e da ocorrência de queimadas em Minas Gerais para acessar a vulnerabilidade da paisagem às mudanças globais. A cobertura do solo foi analisada através de mapas de vegetação de três regiões (norte, sul e oeste), considerando variações temporais e de pressões antrópicas na fragmentação da paisagem, obtida por índices derivados de análise fractal. O regime de queimadas foi estudado pelo Índice Normalizado de Fogo (NFI), obtido de produtos de sensoriamento remoto (ASTR, TRMM e NOAA), distribuído em uma grade de 0.5^{o}, de 1997 a 2006. Uma base de dados de 1981 a 2000 foi utilizada para o estudo da influência de eventos de El Niño na ocorrência de queimadas. Anomalias de temperatura e precipitação de três bases de dados climáticos (CRU TS 2.1; CNRM-CM3 e estações climatológicas) foram correlacionadas a anomalias de NFI para estudar o risco climático da ocorrência de queimadas no futuro. Os resultados demonstraram que o cerrado em Minas Gerais foi substituído por cultivos agrícolas. A estrutura da paisagem pode ter sido modificada pela agricultura, que foi identificada como o principal fator capaz de alterar os padrões de cobertura do solo nas três regiões estudadas. As queimadas foram mais freqüentes nas áreas de agricultura, sendo correlacionadas com a variabilidade do clima e a eventos de El Niño. Mais de 90% do total anual de queimadas ocorreram na época seca. Detectou-se a maior freqüência de focos de queimada no norte de Minas Gerais, na área sob alta pressão antrópica e nas fronteiras de cerrado e agricultura. Com base nas regressãoes de anomalias de temperatura e de precipitação, observou-se que o risco de ocorrência de queimadas, para as próximas décadas, tende a aumentar.

Palavras-chave: freqüência de queimadas, fragmentação da paisagem, anomalias climáticas, dinâmica da paisagem.

---

* Comitê Orientador: Prof[a]. Dr[a]. Angela Maria Soares (Orientadora), Dr. Serge Rambal - DREAM/CEFE/CNRS (Co-orientador).

1 INTRODUCTION

In the last century, the studies on the effects of global changes over the land cover patterns and fire occurrence were mainly concerned with the distribution of the species in space and the abundance of species in time. The results of these studies addressed the loss of biodiversity as the major threat caused by landscape fragmentation in response to global changes (Hargis et al., 1998; Southworth et al., 2004). Lately, the attention to the role that land cover has in defining biophysical processes within the landscape and its relation to functional processes at the ecosystem level has increased. This concern has to do with the possibilities of loss of ecosystem services and of feedback from the current trends in CO_2 concentrations and warming (Li, 2002; Baldí et al., 2006; Thielen et al., 2008; Garrigues et al., 2008).

It has been demonstrated that changes in land cover patterns, either in time or space, can be correlated with disturbances in the energy, water, and nutrient fluxes across the landscape. Often, the changes in these patterns can largely influence the processes by which ecosystems take and return carbon from the atmosphere, including burnt biomass (Mouillot et al., 2002; Mouillot et al., 2005; Southworth et al., 2004; Garrigues et al., 2008; Thielen et al., 2008). The understanding of those relationships can provide important information for the assessment of vulnerability, and can be used as complementary tools in landscape simulation exercises by enhancing the risk and response (resistance and resilience) approaches of vegetation to weather variability (Saunders et al., 1991; Southworth et al., 2004; Baldí et al., 2006).

An important output of land use changes and weather variability is biomass burning, which not only results in modification of the carbon stock in the landscape components, but also affects the atmospheric properties, related to variations in albedo and hydrological features, thereby affecting the biochemical cycles at the regional level. However, the relationship of fire occurrence to climate variability has been somewhat neglected in some landscape dynamics models and in the assessment of landscape vulnerability (Pereira et al., 2000; Thonicke et al., 2001; Santos et al., 2003; Bond et al., 2005; Mistry, 2005; Cernusak et al., 2006; Di Bella et al., 2006; Beerling & Osborne, 2006).

Within such considerations, our underlying hypothesis is that the landscape structure of Minas Gerais, and thus biomass burn, are non-random processes resulting from a complex interplay of anthropogenic pressures and weather variability. The objectives of this study were: (1) to characterize spatial patterns of land cover fragmentation and fire occurrence related to anthropogenic pressure and weather variability in Minas Gerais (2) to verify and forecast the risk of fire occurrence associated to weather extremes in Minas Gerais and (3) generate information to be used in the assessment of landscape vulnerability to global changes in Minas Gerais.

2 MATERIAL AND METHODS

2.1 STUDY SITES AND LAND COVER ANALYSIS

Three sites were selected in the state of Minas Gerais, southeast Brazil, for this study (Figure 1): the north, south and west. The three sites laid over deep red / red-yellow dystrophic soils with medium (approximately equal parts of sand, silt and clay) to clayey (between 35 and 60% clay and equal parts of silt and sand) texture. The mean altitude in the northern region is 466 m, and 1215 m and 873 m in west and south sites, respectively. Thematic maps of the study sites were generated from land cover classification over Landsat TM images. To the north site, one image from 2003, at a spatial resolution of 30m (Figure 2A) (Laboratório de Estudos em Manejo Florestal – Universidade Federal de Lavras - LEMAF-UFLA http://www.dcf.ufla.br/LEMAF-UFLA/); to the west site, four images were used: 1973 and 1980, spatial resolution of 80m; 1993 and 2002, spatial resolution of 30m (Figure 2B, C, D, E) (Laboratório de

Geoprocessamento - Empresa de Pesquisa Agropecuária de Minas Gerais - GEOSOLOS-EPAMIG - http://www.epamig.br/Geosolos-EPAMIG/). In the south region, one image from 2005, spatial resolution of 10m, was used (Figure 2F) (GEOSOLOS-EPAMIG). A 2004 map of anthropogenic pressure over natural vegetation in Brazil, from the Instituto Brasileiro de Geografia e Estatística (IBGE - http://mapas.ibge.gov.br/), was also used in our analysis (Figure 2A).

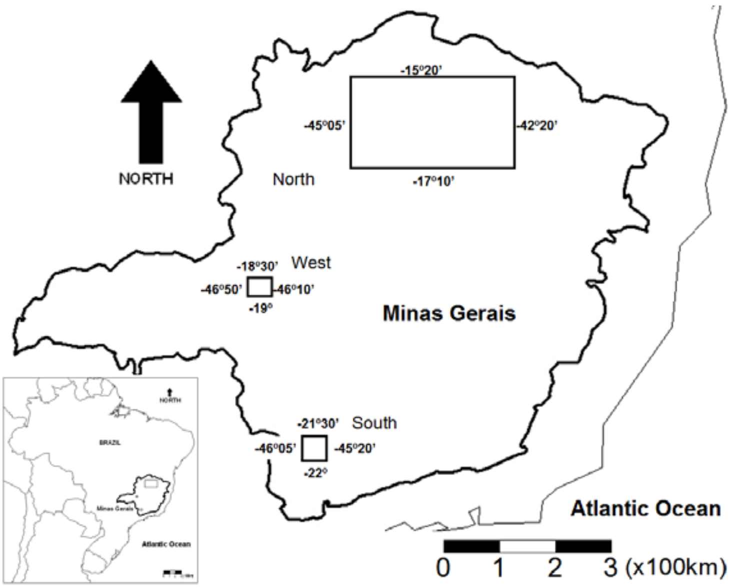

Figure 1 – The location of the study sites in Minas Gerais, Brazil.

The vegetation maps were analyzed to verify fragmentation patterns of the land cover classes by a discrete set of metrics, using the FRAGSTATS 2.0 software (http://www.umass.edu/landeco/research/fragstats/fragstats.html). The metrics used were: patch density (PD), landscape patch index (LPI), interspersion & juxtaposition index (IJI), modified Simpson's evenness index (MSEI), normalized landscape shape index (NLSI) and percentage of landscape per class (PL). NLSI, LPI, PL and PD provided indications of the degree of fragmentation for different land cover types. MSEI and IJI provided information about the shape and interspersion of patches. Because the use of these indexes is not an average value, such as the traditional statistical methods, but rather a count and so not skewed by outliers, they are good descriptors of the entire landscape, and not just the extremes (Hargis et al., 1998).

The following is a brief description of the metrics and its theoretical measurement and significance:

(a) Patch density (PD, patches $100ha^{-1}$): It is equal to the number of patches of the corresponding patch type, for class level; or the number of patches in the landscape, for landscape level, divided by total landscape area. The unit used was the number of patches per 100 hectares. This index indicated a fundamental aspect of landscape, since it expresses the number of patches on an area basis, which facilitates comparisons among landscapes of varying size. Higher values of patch density are related to smaller patch size and more fragmented landscape.

(b) Percentage of Landscape (PL, %): Gives the percentage of the landscape comprised by the corresponding patch type. The percentage of landscape quantifies the proportional abundance of land cover type in the landscape. It is a measure of landscape composition.

(c) Landscape patch index (LPI, %): area of the largest patch in each class, expressed as a percentage of total landscape area. For landscape level, equal to the area of the largest patch in the landscape, divided by total landscape area, converted to percentage. It is a measure of dominance.

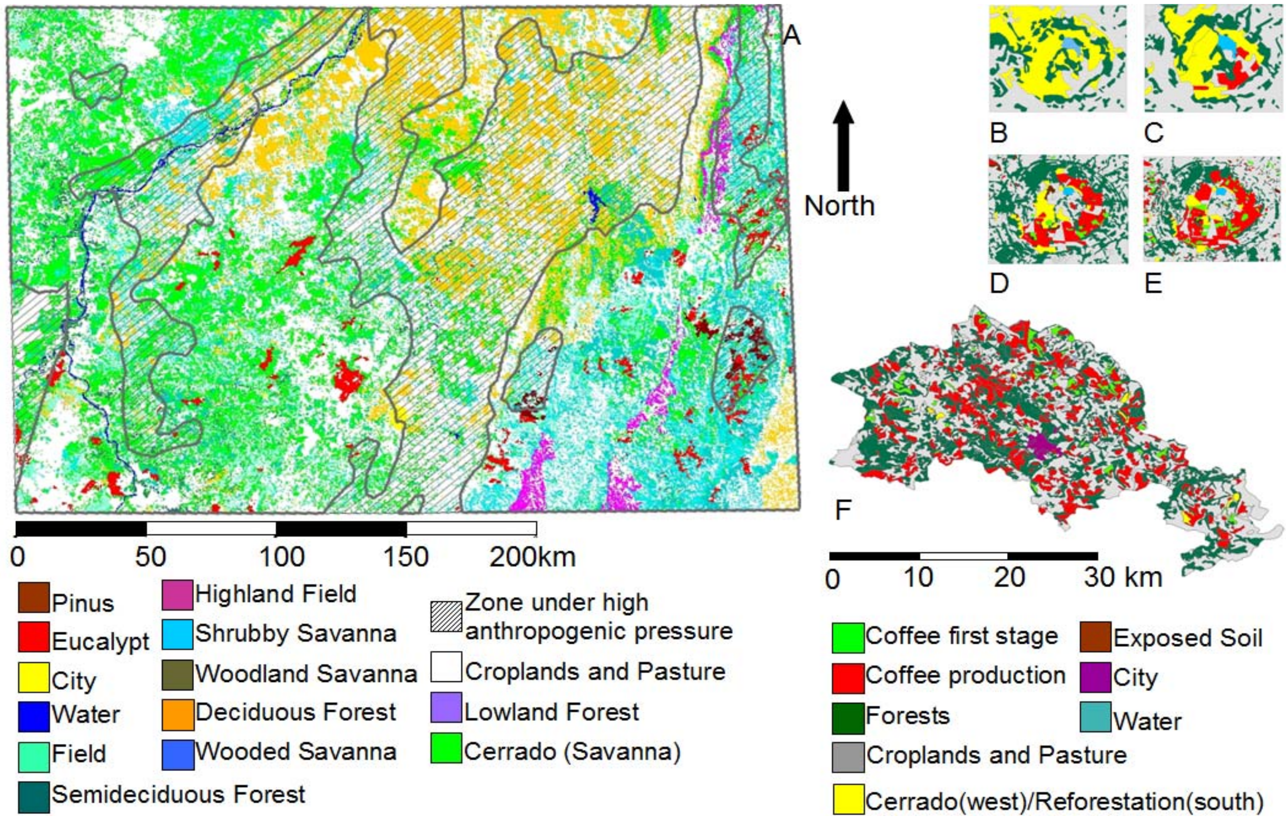

Figure 2 – The land cover maps used in the analysis of fragmentation in the three study sites in Minas Gerais. A-north, 2003 (LEMAF-UFLA and IBGE). B, C, D and E –west in 1973, 1981, 1993 and 2002, respectively (Geosolos-EPAMIG). F – south, 2005 (Geosolos-EPAMIG).

(d) Modified Simpson's Evenness Index (MSEI): Reports the proportional abundance of each patch type. This metric is expressed in a way that an even distribution of area among patch types results in maximum evenness. The evenness given by this index is the complement of dominance.

(e) Normalized Landscape Shape Index (NLSI): It averages the complexity of the landscape as a whole, ranging from zero to one, providing a measure of class aggregation or clumpiness. It equals 0 when the landscape consists of a single square or maximally compact patch (almost square, more simple form) of the corresponding type; NLSI increases as the patch type becomes increasingly disaggregated and is 1 when the land cover class is maximally disaggregated (more complex form).

(f) Interspersion & juxtaposition index (IJI, %): degree of interspersion or intermixing of patches of the class with all other classes. The values approach 0 when the distribution of adjacencies among unique patch types becomes increasingly uneven and equals 100 when all patch types are equally adjacent to all other patch types.

2.2 FIRE REGIME

2.2.1 Datasets and data analysis

The assessment of the variability of fire regime in Minas Gerais was made by the fire frequency (number of fires that occur per unit time at a given point). Three datasets were obtained by different remote sensing products of fire detection: the **A**long **T**rack **S**canning **R**adiometer (ATSR), the **N**ational **O**ceanic and **A**tmospheric **A**dministration-**A**dvanced **V**ery **H**igh-**R**esolution **R**adiometer (NOAA – 14/ AVHRR) from the Fire Group of the **C**entro de **P**revisão de **T**empo e **E**studos **C**limáticos **-** **I**nstituto **N**acional de **P**esquisas **E**spaciais (INPE-CPTEC **-** www.cptec.inpe.br), and the **T**ropical **R**ainfall **M**easuring **M**ission satellite **V**isible and **I**nfrared **S**canner (TRMM–VIRS). The distribution of recent fire activity from ATSR dataset showed 1km of spatial resolution, from January 1997 to December 2005. From NOAA-AVHRR we integrated data from the afternoon and night passes of 1.2 km^2 spatial resolution, from June 1998 to December 2006. The TRMM dataset had a spatial resolution of 1^o, from January 1997 to December 2005. A fourth dataset consisted of published data (Riaño et al., 2007) of the fire frequency detected by NOAA-AVHRR 11 and 14 monthly aggregated from July 1981 to December 2000 in a spatial resolution of 1000km. This dataset was used to study the influence of El Niño southern oscillation episodes (ENSO) over the fire regime in Minas Gerais.

The ATSR, TRMM and NOAA datasets were processed in monthly integrations within 0.5° cells over Minas Gerais. For Riaño's dataset, we analyzed the fire frequency into the original grid cell of 1000 km x 1000 km, which covered part of Brazilian southeast and central-west. The datasets were transformed by the normalized fire index (NFI) (1)

$$NFI = [Ff_{ij} \times (Ff_{maxj})^{-1}] \quad (1)$$

where: NFI is the Normalized Fire Index, Ff was the fire frequency in a given time ($_i$) in a given grid cell ($_j$), Ff_{max} was the maximum fire frequency observed in the analysis period of each dataset, at the respective grid cell under analysis. We calculated the standard error among grid cells and compared the average NFI by the test of Tukey ($P<0.05$). We also explored the fire regime in the north, south and west study sites of Minas Gerais, applying the same protocol of NFI in a 6 x 6 cell grid (3^o x 3^o), considering the highest NFI in each region.

2.2.2 Weather variability and fire risk

Monthly anomalies of precipitation and temperature during the observation period were calculated by subtraction of the normal value (1961 to 1990) from the observed value. For the calculation of the NFI anomalies, we selected 2005 as a normal year for fire occurrence in Minas Gerais, due to the similarities with normal weather characteristics. The NFI anomalies were obtained as percentage in relation to normal. The values of NFI anomaly were correlated with anomalies of mean air temperature and precipitation derived from three climatic datasets: CRU TS 2.1 (Mitchell & Jones, 2005), CNRM-CM3 (Salas-Melía et al., 2005) and weather stations from the **I**nstituto **N**acional de **M**eteorologia (INMET) (http://www.inmet.gov.br/html/rede_obs.php) and from CPTEC-INPE (http://satelite.cptec.inpe.br/PCD/pcd.jsp?uf=12), from the three study sites: south **-** Lavras, Machado and Itajubá, north – Januária and Salinas, and west **-** Araxá and Patrocínio. The regression models between weather anomalies and NFI anomalies were tested by the *t*-test (P<0.01). From the prediction of the extreme temperature and precipitation from 1900 to 2100 and the regression equations of the NFI anomalies with climatic anomalies, we composed a framework to predict the climatic risk of fire occurrence in the XXI century (from 2005 to 2100) (Figure 3).

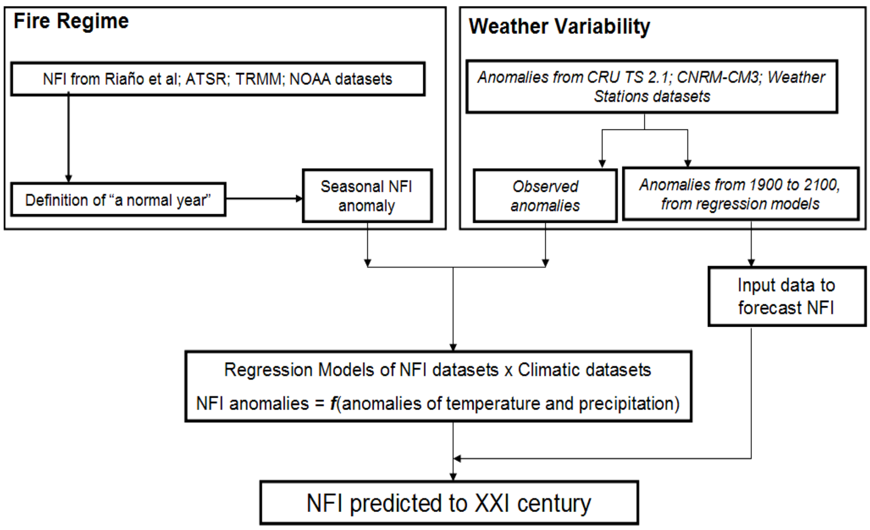

Figure 3 – Framework used to forecast climatic fire risk in Minas Gerais in the XXI century, based in regression equations of NFI, temperature and precipitation anomalies of different data sources.

3 RESULTS

3.1 LAND COVER ANALYSIS

3.1.1 Landscape structure

The highest PD values were observed in the zones under low (3.4 patches 100ha^{-1}), under high (2.7 patches 100ha^{-1}) anthropogenic pressure in the north of Minas Gerais and in the west site in 2002 (2.9 patches 100ha^{-1}) (Table 1). The site in the south of the state and in the west, in the years 1973 and 1981, showed the lowest PD values (0.3 to 0.5 patches 100ha^{-1}). The analysis of PD showed that, in general, the fragmentation of the landscape has increased in time in the west region (from 0.3 to 2.7 patches 100ha^{-1} from 1973 to 2002). Confirming this observation, the LPI analysis showed that the west of Minas Gerais was largely dominated by a single land cover class in 1973 (Table 1). This domination decreased with time, and in 2002, this site showed a more heterogeneous land cover structure. The value observed in 2002 in the west of Minas Gerais was similar to the value observed in the south. In the study site in the north, the highest value of LPI was observed in the areas under high anthropogenic pressure.

Table 1 - Patch density (PD, patches 100ha^{-1}), Landscape patch index (LPI, %), Interspersion & Juxtaposition Index (IJI, %) and Modified Simpson's Evenness index (MSEI) observed in the studied sites of the landscape of Minas Gerais: west 1973; west 1981; west 1993; west 2002; south 2005and north 2003.

Lansdcape	Date	PD	LPI	IJI	MSEI
West	1973	0.31	38.38	66.11	0.78
	1981	0.27	21.35	59.22	0.67
	1993	0.97	15.54	44.99	0.57
	2002	2.70	3.76	45.46	0.52
South	2005	0.52	3.75	44.11	0.53
North HAP*	2003	2.93	9.20	60.27	0.06
North LAP**	2003	3.34	4.52	60.20	0.12

*High antropogenic pressure, 2004.
**Low anthropogenic pressure, 2004.

The west in 1973 showed the highest IJI values with a large connectivity between the classes in this year (Table 1). Our analysis indicated that the intermixing of different land cover decreased throughout the analyzed years in this site. The values from 1993, 2002 and the ones observed in the south of the state were similar. No difference was observed in the IJI values in the two zones in the north of the state. In the west of Minas Gerais, the MSEI decreased in time, indicating higher eveness of patches in 1973 than in 2002. The value observed in this date was similar to the value observed in the south of the state, indicating that the patches of diverse land cover were distributed randomly in the landscape. The values observed in the north of Minas Gerais were very low, suggesting an uneven distribution of the patches in the landscape.

3.1.2 Characteristics of land use and land cover

In general, the studied sites were dominated by anthropogenic land uses (croplands and pasture and coffee agriculture), which accounted for at least 40% of the landscapes (Tables 2 and 3). The water bodies occupied less than 2% and the urban areas less than 1% of the analyzed landscapes. In the south site, the reforestation areas occupied only 0.66% of the landscape. The areas occupied by forests, in the west site, were almost constant in time, representing an average value of 23% of landscape. However, it was possible to observe a great loss of cerrado in this site in time: in 1973 cerrado covered almost 35% of the landscape, and in 2002, the coverage was of 3.4%. Simultaneously with the decrease in the areas occupied by cerrado, there was an increment in the areas used for coffee agriculture as well as an increment in the croplands and pasture. The lands used for coffee agriculture increased from zero to 21% and croplands and pasture from 40%, in 1973, to 50%, in 2002. In the south site, 66% of the landscape was used for agriculture (croplands and pasture– 43% and coffee-

23%). Forests occupied 32% of the landscape and urbanization corresponded to 1% of the area.

Table 2 – Percentage of landscape occupied by each of the land cover classes in the sites in the west and south of Minas Gerais.

Land cover class	WEST				SOUTH
	1973	1981	1993	2002	2005
Forest	23.02	23.37	24.67	23.23	32.17
Croplands and pasture	40.30	48.04	49.21	50.53	43.00
Coffee First Stage	0.00	0.00	4.02	4.50	2.90
Coffee Production	0.00	4.18	13.55	17.01	20.05
Water	1.27	1.65	0.5	0.46	0.22
Exposed Soil	0.00	0.00	1.95	0.83	0.00
Cerrado/Reforestation	35.40	22.76	6.10	3.40	0.66
City	0.00	0.00	0.00	0.03	1.00

In general, when all land cover classes were considered together, the zone under high anthropogenic pressure in the north of Minas Gerais showed a smaller area covered by cerrado (32% of the landscape) than the zone under low pressure (46% of the landscape) (Table 3). The cerrado vegetation in this zone was higher than in the area covered by croplands and pasture (40%). Among the savanna physiognomies, the cerrado was the most abundant (22% under low and 15% under high anthropogenic pressure). The percentage of landscape under high pressure occupied by deciduous forest was almost 2 times higher than in the zone under low pressure.

The analysis by the NLSI within the studied sites showed low values for all land cover classes, indicating high aggregation of the patches in all the regions (Figures 4A and 5A). The forest class in the west site was less aggregated than the agricultural land cover and the cerrado vegetation. This could be better observed in 1973 and 1981. From 1993 to 2002 it was possible to observe an increment of disaggregation in all the classes of land cover. In the south of the state, the different classes of land cover tended to be highly aggregated (Figure 4A). In the zones of the north of Minas Gerais, the larger land cover classes (croplands and pasture, cerrado and deciduous forest) were more aggregated (Figure 5A). The cerrado was more aggregated in the zone of low anthropogenic pressure as croplands and pasture and deciduous forest showed the highest aggregation in the zone under high anthropogenic pressure. The more disaggregated land cover classes, in both zones, were: field, lowland forest, wooded savanna and semideciduous forest.

Table 3 – Percentage of landscape occupied by each land cover classe in the zones under high and low anthropogenic pressure of the study site at the north of Minas Gerais.

Land cover classification	Anthropogenic pressure level	
	High	Low
Croplands and pasture	44.10	40.10
Cerrado	15.60	22.40
Field	5.00	7.80
Shrubby savanna	7.60	7.40
Decidous Forest	20.44	9.00
Water	0.52	0.40
Semidecidous Forest	1.19	1.80
Wooded Savanna	2.97	6.92
Highland field	0.41	1.33
Eucalypt	1.03	1.90
City	0.26	0.18
Lowland forest	0.21	0.52
Pinus	0.65	0.15
Woodland savanna	0.00	0.10

The LPI showed that in the west site, the agricultural land uses and cerrado were the land cover types dominating the landscape in 1973 and 1981 (Figure 4B). In 1993 the coffee agriculture and forest were the dominant land cover classes. In 2002 the agricultural uses had increased, whereas forests had decreased their occupation in the landscape. Cerrado, similar to what happened to the forest, had decreased in time in the west site. The south site and the zones in the north of Minas Gerais, showed agricultural uses as the major land cover type. The zone under low anthropogenic pressure showed lower LPI for the croplands and pasture, when compared to the zone under high pressure, whereas the inverse was observed for cerrado (Figure 5B).

The values of PD, in general, increased in all land cover classes in the west site, from 1973 to 2002, indicating that the landscape became more fragmented and with smaller patches (Figure 4 C). The forest was the ecosystem with higher fragmentation level in the west and south sites. The PD of the land cover classes field, croplands and pasture, semideciduous forest and wooded savanna, in the zone under high anthropogenic pressure, in the north of Minas Gerais, was lower than the density observed in the zone under low anthropogenic pressure (Figure 5C).

In general, in the west site, the IJI was almost constant for cerrado, revealing that its neighbor patches remained constant along the years (Figure 4D). For the other land cover classes, the values of this index tended to decrease from 1973 to 2002, indicating that the number of different neighbor patches increased. In the south, it was observed that coffee agriculture, reforestation, city and water showed the highest values of IJI. In general, the IJI values of the diverse land covers were similar between the two studied zones in the north of Minas Gerais (Figure 5D). The highland field, field, woodland savanna and deciduous forest showed restrict connectivity with other land cover types in the north of Minas Gerais.

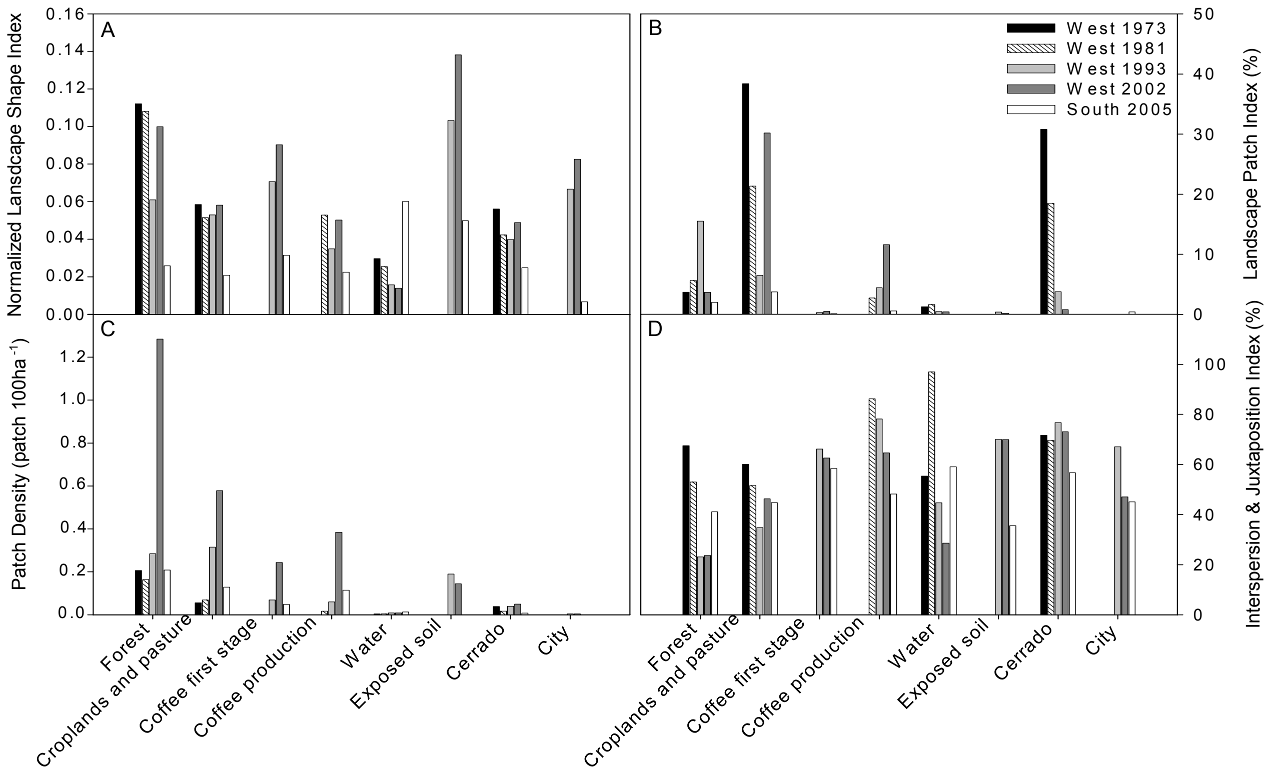

Figure 4 – (A) Normalized landscape shape index (NLSI); (B) Landscape patch index (LPI); (C) Patch density (PD) and (D) Interspersion & juxtaposition index (IJI) observed in the land cover classes of the studied landscapes in the west and south of Minas Gerais. The “cerrado” in the south corresponds to “Reforestation”.

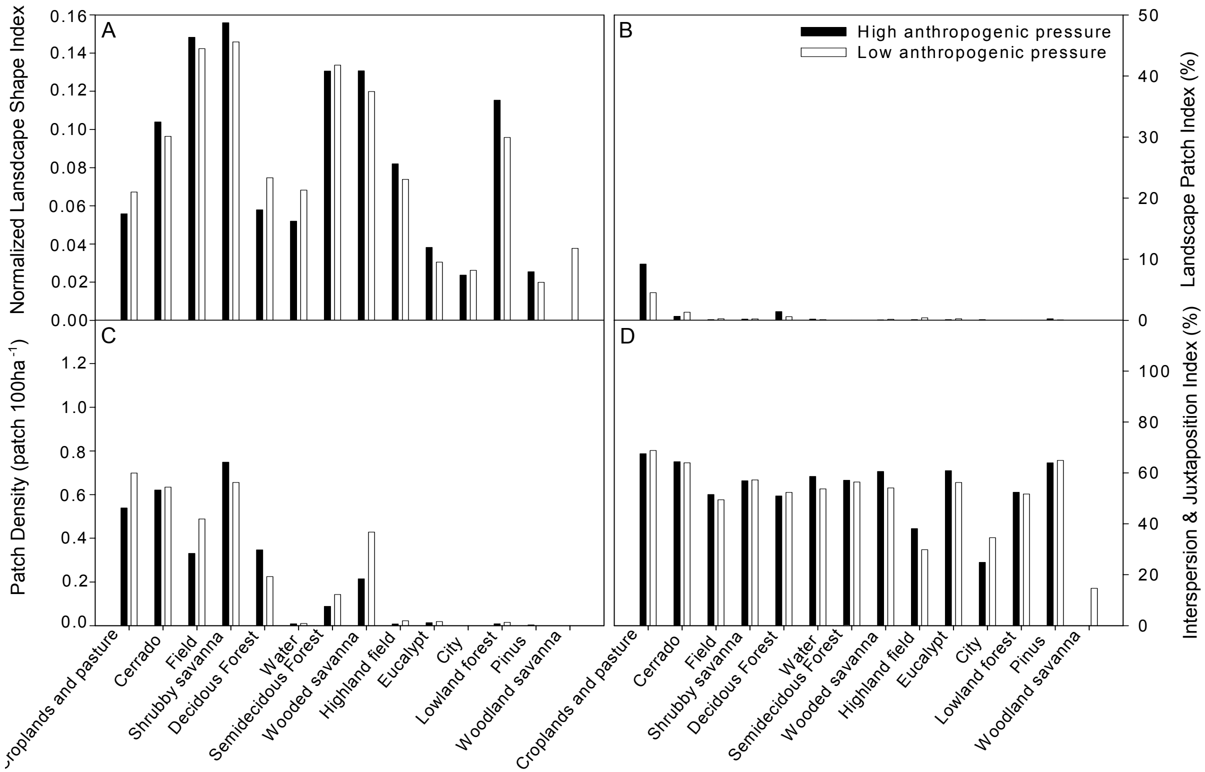

Figure 5 – (A) Normalized landscape shape index (NLSI); (B) Landscape patch index (LPI); (C) Patch density (PD) and (D) Interspersion & juxtaposition index (IJI) observed in the zones under high and low anthropogenic pressure in the studied landscape in the north of Minas Gerais.

3.2 FIRE REGIME

3.2.1 Spatial pattern of fire occurrence in Minas Gerais

The spatial distribution of NFI was similar in time, to most of the fires occurring in the same grid cells every year. Most of the ignitions occurred in the north and south regions of Minas Gerais (Figure 6). The NOAA dataset indicated that fires spread throughout the territory of Minas Gerais, but the spots concentrated around the northern region, progressively spreading out towards the east and to the southwest regions (Figure 6B). Most of the territory showed NFI values lower than 0.40. Similar spatial distribution of fire could be observed by the TRMM dataset, which also demonstrated that the south and north regions of the state showed intense biomass burning (Figure 6C). However, the NFI values of TRMM in most of the state, on an annual basis, were lower than 0.2, which corresponded to 50% of the NFI values observed by NOAA. The ATSR dataset also showed lower fire density than the one observed in the NOAA dataset (Figure 6A).

The three datasets indicated great biomass burning activities corresponding to agricultural fires for clearing activities or cultural operations. In the southern border with São Paulo state, probably linked to the harvesting of sugarcane for the local alcohol industry. To the northwest region, ignitions were also denser in some pixels corresponding to the state of Goiás and Tocantins where, in general, intensive clearing activities were concentrated. We observed that the grid cells with higher fire incidence, at the north of Minas Gerais, could be associated to the zone under high anthropogenic pressure. The datasets showed that most of ignitions occurred on the border lines of the zones under low and high anthropogenic pressure, in areas of cerrado and deciduous forests. These frontiers would be more susceptible to the ignitions in the fire-prone cerrado vegetation, probably as a result of clearing activities during the dry season in this region.

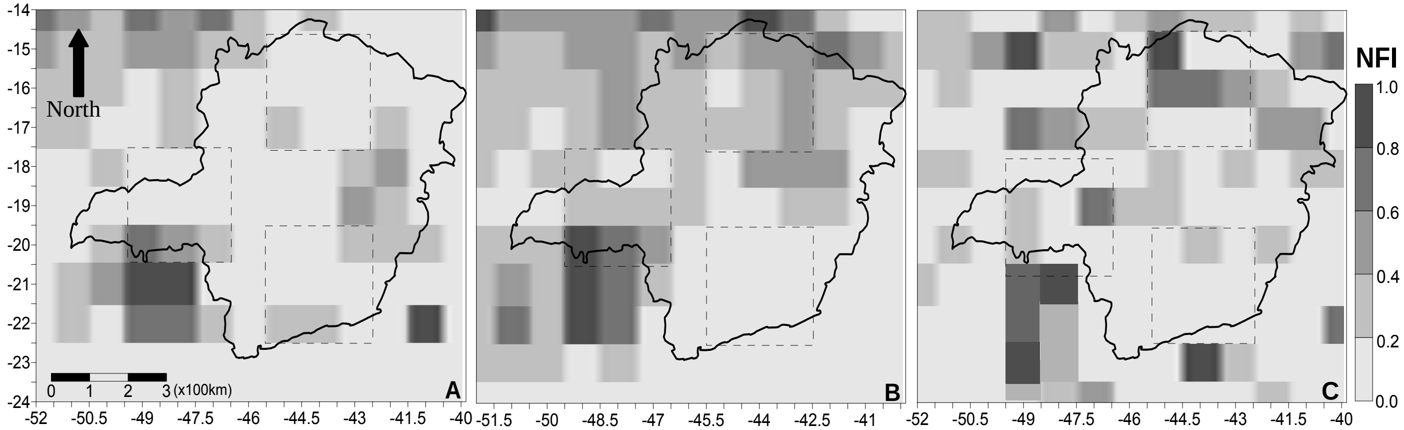

Figure 6 - Geographical distribution of the normalized fire index (NFI) from the datasets of (A) ATSR, (B) NOAA and (C) TRMM during the evaluation periods in a 0.5° x 0.5° grid over Minas Gerais. The squares indicate the areas used for the fire occurrence study in the north, south and west regions of Minas Gerais.

3.2.2 Temporal distribution of fire frequency in Minas Gerais

Based on the different datasets used in this study, we observed that the pattern of burnt surface in Minas Gerais was related to the seasonal and inter-annual weather variability. Most of the ignitions, whatever the dataset, occurred at the end of the dry season (Figures 7A, D). The weather conditions in this period could be characterized by soil drought and rising air temperatures (August, September and October). In general, the data of the four datasets showed peaks of NFI correlated with ENSO episodes (Figures 7E, F). The longest dataset (Riaño et al., 2007) showed higher values of NFI in years under ENSO influence in relation to years without ENSO events (Figure 8A). The increment in fire occurrence during ENSO years was accompanied by higher temperatures and reduction of precipitation in the dry season in relation to normal values in the CRU TS 2.1 weather dataset (Figures 8B).

Within the same period, no differences of NFI among the datasets was observed ($P>0.05$) in Minas Gerais (Figures 7D, E). The four datasets demonstrated a small density of fires during the wet season (November to March), which represented only 10% of the total amount of annual ignitions. The fire frequency started to increase from June, marking the onset of the fire season in Minas Gerais. The Riaño and the ATSR datasets showed peak of fire frequency in August, September and October. The TRMM dataset showed the maximum fire frequency in September and the NOAA dataset showed the maximum values in September and October. The years with the highest NFI values in the NOAA dataset were 1998, 2001 and 2002 (Figure 7E). In the ATSR and TRMM datasets, the highest value of NFI was observed in 1998. In the 20 years of observational data of Riaño et al. (2007), the highest values of NFI occurred in 1985, 1995, 1996 and 1998 (Figure 7F).

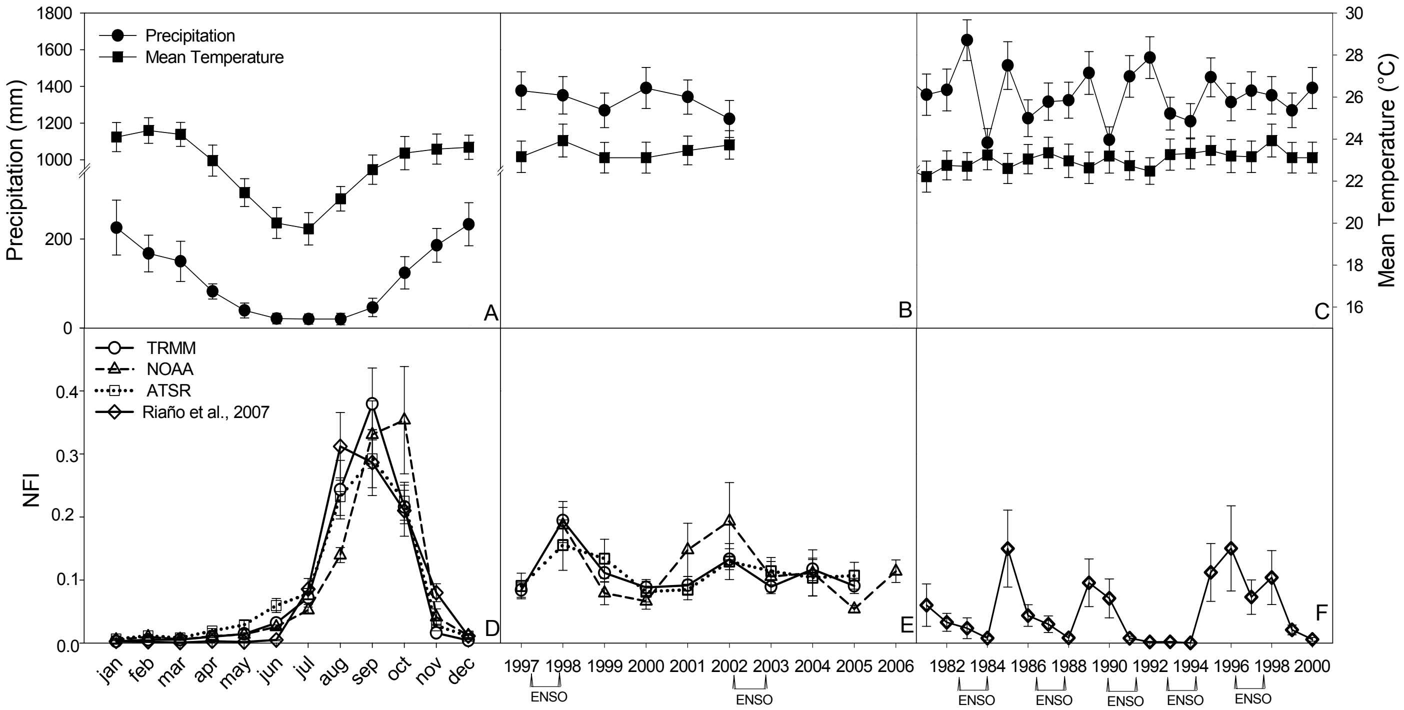

Figure 7 – Montly (A) (from 1961 to 1990, n=30) and annual (B and C) (n=12) values of precipitation and mean air temperature from the CRU TS 2.1 in Minas Gerais; and monthly (D) and annual (E and F) distribution of the Normalized Fire Index (NFI), in Minas Gerais from NOAA (n=9) (△), ATSR (n=9) (□), TRMM (n=9) (○) and Riaño et al. (2007) (n=20) (◇) datasets. Values are average ± standard error.

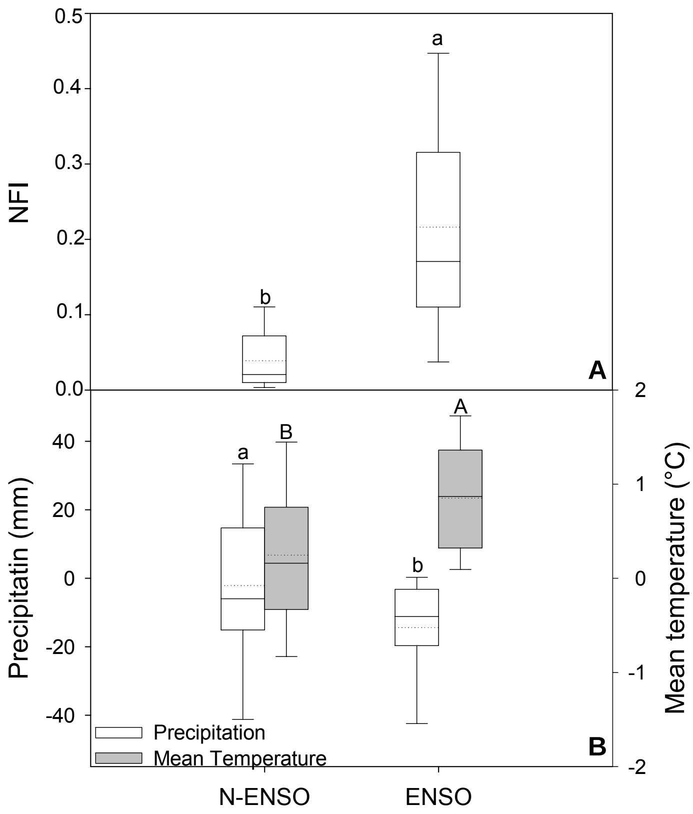

Figure 8 – (A) Distribution of the Normalized fire index (NFI) and (B) of precipitation and temperature anomalies observed in Minas Gerais in the months of the dry season during year under ENSO (n=48) and without ENSO (N-ENSO n=32) influence. The NFI values were obtained from the Riaño et al. (2007) dataset and the weather anomalies were extracted from the CRU TS 2.1 dataset. The solid and the dotted lines in the box plots indicate the median and the average of the raw data, respectively. The top and bottom of the boxes indicate the 25th and the 75th percentiles, the whiskers above and below the boxes indicate the 90th and 10th percentiles of the normal distribution of the raw data. Categories that do not share the same letter, in the horizontal sense, are significantly different at P<0.05.

In general, comparing the fire regime in the three regions in Minas Gerais, we observed that the average fire frequency per grid cell in the west was higher than the fire frequency in the other two regions (Figure 9). On the annual basis, the NOAA and ATSR datasets indicated higher burned surface in this site throughout the study period (Figures 9B, D). In the south of Minas Gerais, the NFI was higher in the months of the dry season (August, September and October), with no differences in the other months (Figures 9A, C, E). The values observed in the TRMM dataset to the north, south and west regions were more similar (Figures 9E, F).

The incidence of fire was almost constant in the west of Minas Gerais along the evaluation period; however the TRMM dataset detected less burnt surface than NOAA and ATSR in this region (Figure 9F). In the south of the state, the years with highest values of NFI for the ATSR dataset were 1999 and 2002 (Figure 9B); for the NOAA dataset, the year with highest NFI were 1999, 2002 and 2003 (Figure 9D), whereas for TRMM dataset only 1999 (Figure 9F). In the north of Minas Gerais, 1998 was the year with highest burnt surface, detected in the 3 datasets, however, the ATSR dataset also showed high NFI values in 2000 and 2005; and the NOAA dataset indicated higher values in 2002 and 2003.

3.2.3 Weather variability and fire regime: climatic risk to fire occurence

In general, the north was warmer and drier than the south and west of Minas Gerais. Nonetheless, the west was warmer than the south (Figure 10). In the months of the dry season (April to September) the precipitation of the three regions was similar, reaching the minimum values (Figure 10A); however, the amount of precipitation observed in the months of the wet season in the north were lower than the values observed in the south and west regions. For temperature, the values of the dry season observed in the north of Minas Gerais were as high as the temperatures observed in the wet season in the south and west (Figure 10B). The south was colder than the west from April to June, with similar temperatures for the other months.

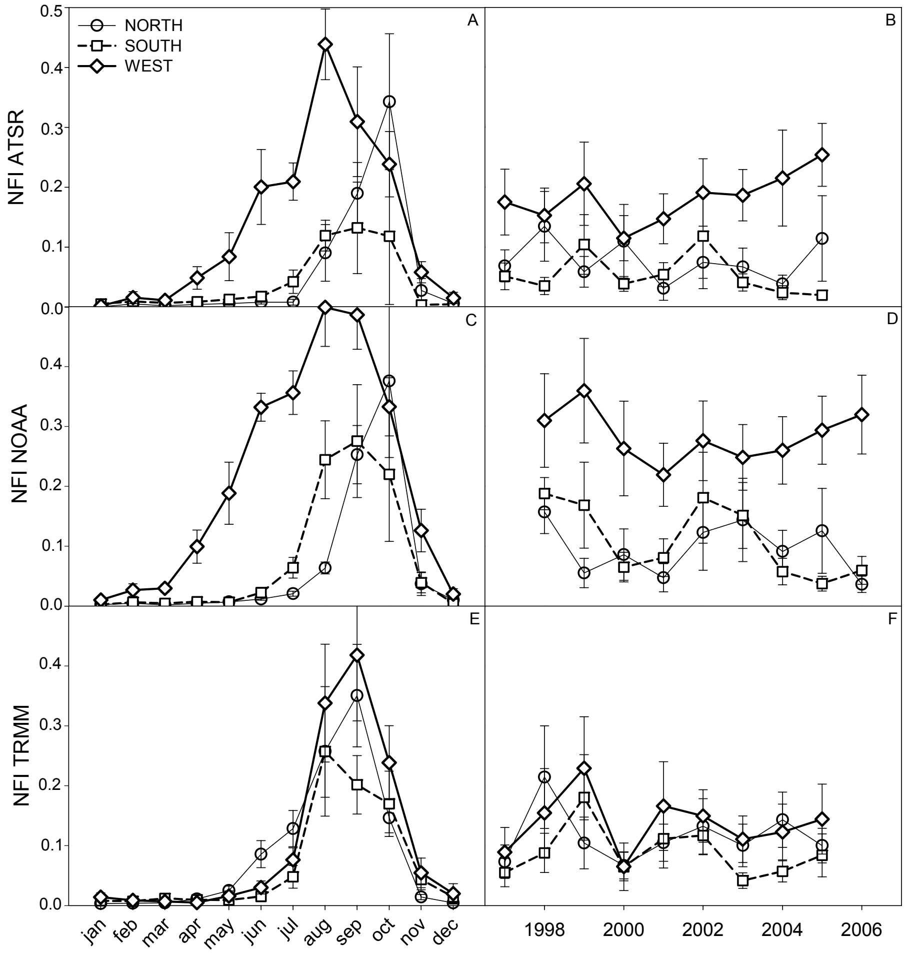

Figure 9 – Montly (n=10) and annual (n=12) distribution of the Normalized Fire Index (NFI), in the north (O), south (☐) and west (◇) of Minas Gerais from ATSR (A, B), NOAA (C, D), and TRMM (E, F) datasets. Values are average ± standard error.

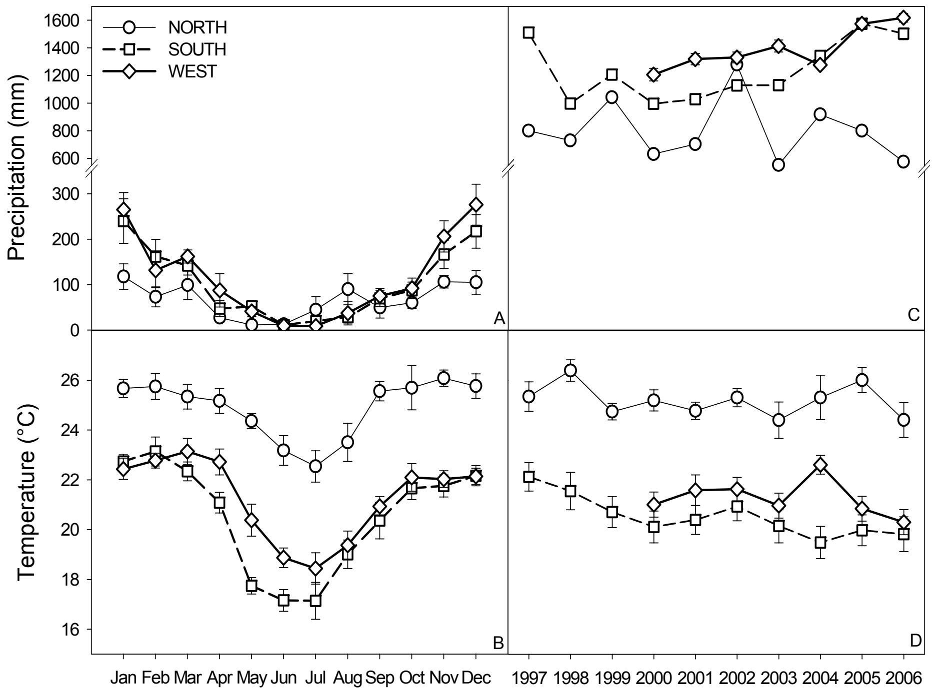

Figure 10 – Montly (n=10-north and south and n=7-west) and annual (n=12) distribution of precipitation (A, C) and mean air temperature (B, D), in the north (○), south (□) and west (◇) of Minas Gerais from weather stations datasets. Values are average ± standard error.

Considering the whole Minas Gerais territory as well as the three study regions, the regression equations of seasonal anomalies of NFI in function of the precipitation and temperature anomalies from the CRU TS 2.1, CNRM-CM3 and weather station datasets indicated, in general, that the increment in the air temperature and the decrease in the precipitation had a positive effect on the fire occurrence during the wet and the dry seasons (Figure 11). However, the effects of weather anomalies in the dry season showed a greater effect in increasing anomalies of NFI. Reduction in the monthly precipitation of -50mm and increasing of the air temperature by +1.5^{o}C from June to September represented, in general, a risk of increase in the NFI values ranging from 30 to 50%.

The regression equations obtained in the wet season were similar among the different weather and fire datasets. The regressions obtained for precipitation in the dry season were similar for CRU TS 2.1 and CNRM-CM3 datasets (Figures 11A, C). For temperature, the equations of CNRM-CM3 and weather stations were similar (Figures 11B, F). The equations in figure 11 were used as an exercise to calculate the climatic risk of fire occurence in Minas Gerais in function of temperature and precipitation variability. The starting point for this approach was the calculation of maximum and minimum seasonal temperature and precipitation anomalies from 1900 to 2100, using the equations showed in table 4. Those regressions were based on values of the 10th and 90th percentiles of the seasonal distribution of anomalies in function of years. After, we calculated the NFI anomalies based on the maximum and the minimum seasonal weather anomalies.

In the next step, we summed the values of the NFI anomalies; however, we considered the risk of the temperature and precipitation in increasing the NFI anomaly. Temperature increment and precipitation decrease were considered positive effects, and temperature decrease and precipitation increment, negative effects in the calculation of the climatic fire risk. Finally, the summation process was adjusted by the seasonal effect in the annual NFI anomaly, considering that the dry season is responsible for 90% of the annual fire occurrence. The final equations to predict annual NFI anomaly (A_{NFI}), according to the climatic datasets CRU TS 2.1 (CRU), CNRM-CM3 (CNRM) and weather stations (WS), were:

$$A_{NFI\ CRU}=0.1(NFI_{tmax}+NFI_{tmin}+NFI_{pmin}-NFI_{pmax})+0.9(NFI_{tmax}+NFI_{tmin}+NFI_{pmin}-NFI_{pmax}) \quad (2)$$

$$A_{NFI\ CNRM}=0.1(NFI_{tmax}+NFI_{tmin}-NFI_{pmin}-NFI_{pmax})+0.9(NFI_{tmax}+NFI_{tmin}-NFI_{pmin}-NFI_{pmax}) \quad (3)$$

$$A_{NFI\ WS}=0.1(NFI_{tmax}+NFI_{tmin}+NFI_{pmin}+NFI_{pmax})+0.9(NFI_{tmax}+NFI_{tmin}-NFI_{pmin}+NFI_{pmax}) \quad (4)$$

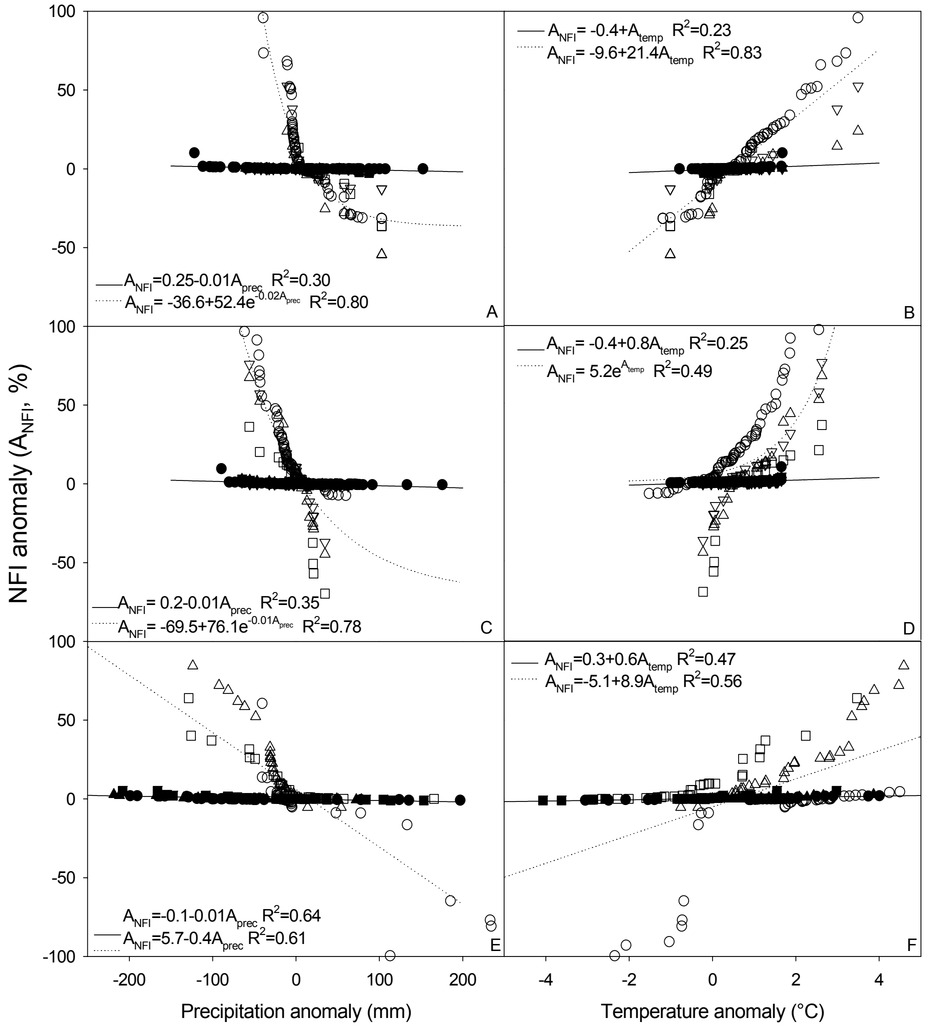

Figure 11 – The relationships of NFI anomaly and precipitation and temperature anomalies, observed in the wet (close symbols, solid lines) and in the dry (open symbols, dotted lines) seasons during the study period in Minas Gerais, using the CRU TS 2.1 (A, B) and CNRM-CM3 (C, D) climatic datasets and the Riaño et al. (2007) (●○), ASTR (△▲), TRMM (▽▼) and NOAA (□■) fire datasets. The relationships in the three regions of the state were obtained by associating weather stations datasets (E, F) with NOAA datasets in the north (●○), south (△▲) and west (□■) of Minas Gerais.

where: NFI_{tmax} and NFI_{tmin}, corresponded to the NFI anomalies calculated in function of the maximum and minimum temperature anomalies and NFI_{pmax} and NFI_{pmin}, corresponded to the NFI anomalies calculated in function of the maximum and minimum precipitation anomalies. The 0.1 factor adjusted the values of the wet season and the 0.9 factor adjusted the values of the dry season for the final fire risk.

Table 4 – The regression equations of maximum (max) and minimum (min) anomalies of temperature (A_{temp}) and precipitation (A_{prec}) in relation to year, obtained from the CRU TS 2.1, CNRM-CM3 and weather stations (WS) datasets, in the wet and dry seasons in Minas Gerais.

Equation	Season	Weather Dataset		
		CRU TS 2.1	CNRM-CM3	WS
A_{temp}max	Dry	-29.4+0.01yr R^2=0.58	-66.3+0.03yr R^2=0.95	-40+0.02yr R^2=0.82
	Wet	-28.7+0.01yr R^2=0.63	-51.4+0.03yr R^2=0.94	-24.8+0.01yr R^2=0.69
A_{temp}mim	Dry	-27.4+0.01yr R^2=0.78	-59.1+0.03yr R^2=0.92	-17.2+0.01yr R^2=0.22
	Wet	-34+0.018yr R^2=0.83	-48.2+0.02yr R^2=0.78	-8.8+0.004yr R^2=0.42
A_{prec}max	Dry	-37.3+0.18yr R^2=0.64	-124.2+0.05yr R^2=0.56	-964.5+0.5yr R^2=0.44
	Wet	-482.6+0.3yr R^2=0.74	-843+0.5yr R^2=0.90	1067-0.5yr R^2=0.26
A_{prec}mim	Dry	31.5-0.03yr R^2=0.57	-64.9+0.01yr R^2=0.72	-10-0.01yr R^2=0.27
	Wet	297.4-0.18yr R^2=0.71	-624.4+0.3yr R^2=0.48	1032-0.6yr R^2=0.61

max – refers to the values of the 75th - 90th percentile and mim – refers to the values of the 10th – 25th percentile of the normal distribution of seasonal anomalies.

The equations 2, 3 and 4 were also fed with observed weather anomalies from the three weather datasets, and the values of annual NFI obtained from the predicted weather anomalies were compared with the values obtained from observed weather anomalies (Figure 12A). In general, we observed high determination coefficients, indicating a good correspondence among the predicted and observed NFI anomalies. The predicted values of NFI based on equations 2, 3 and 4 indicated an increment in the risk of fire occurrence for the next decades (Figure 12B). With exception to the equation 3, based in CNRM-CM3 data, which indicate negative risk on the current climate conditions and risk of 30% in the year 2100, the other two equations (2 and 4) forecasted positive trends for climatic risk of fire occurrence. The CRU equation (2) pointed that the fire frequency in Minas Gerais could double by the end of the century, if the present climate trends are confirmed, with risk of NFI anomaly reaching values near 100%, whereas the weather stations data (4) pointed a risk of fire occurrence reaching 30% of what is observed today.

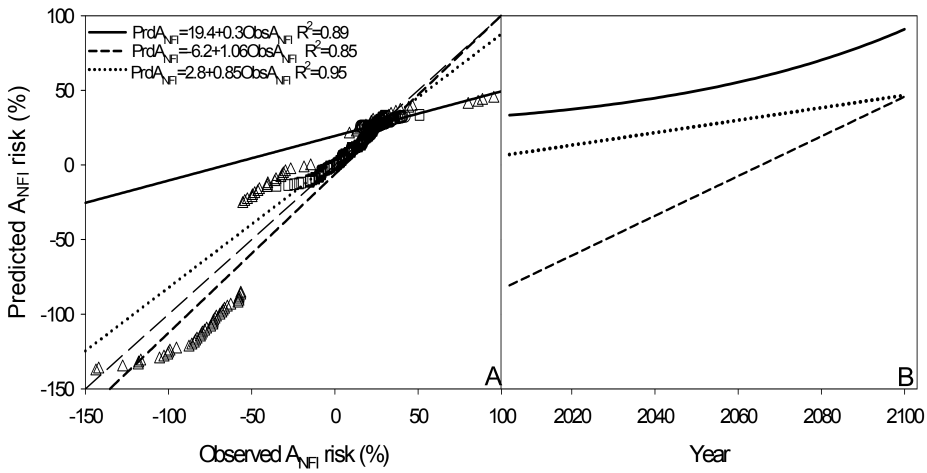

Figure 12 – (A) The relationships between predicted and observed NFI anomalies obtained by precipitation and temperature anomalies of the CRU TS 2.1 dataset (equation 2) (O —), CNRM-CM3 dataset (equation 3) (△ ----) and weather stations (equation 4) (□ ·····), the long-dash is the 1:1 line. And (B) the risk of fire occurrence in terms of NFI anomaly to the next year of the XXI century, calculated in function of precipitation and temperature extremes of the climatic datasets.

4 DISCUSSION

4.1 LAND COVER STRUCTURE

In general, the results of the land cover structure indicated that the landscape of the three study sites in Minas Gerais was highly fragmented, with diverse land cover classes composing an intricate mosaic of heterogeneous vegetation patches. The anthropogenic land uses dominated the three studied landscapes, indicating that natural vegetation was replaced by agricultural land uses over the time. The temporal dynamic of land cover in the west of Minas Gerais demonstrated a pattern of decrease in the area of cerrado together with the increment of agricultural land uses, especially coffee. The analysis of the land cover in the north of Minas Gerais also evidenced a similar pattern of land cover structure. The human activities dominated more than 40% of the landscape, especially in the zone under high anthropogenic pressure, while the remaining 60% was divided by a variety of classes of natural vegetation. Similar dynamic of land cover was observed in other regions of the globe (Hargis et al., 1998; Milhé; 2003; Baldí et al., 2006; Thielen et al., 2008; Körner & Jeltsch, 2008; Garrigues et al., 2008).

In the west of Minas Gerais, the pattern of crop plots superimposed on a cerrado matrix, observed in 1973, gave place to the opposite pattern in 2002, which was small cerrado patches surrounded by a cropland matrix. This pattern could also be observed for cerrado patches in the north of Minas Gerias when the zones under high and low anthropogenic pressure were compared. The rate of conversion of cerrado to agricultural land uses for the west of Minas Gerais was 3.1% year^{-1}, a value almost two times higher than the one observed by Langner et al. (2007) in the conversion of tropical forests to agriculture in the Borneo island (1.7%year^{-1}).

A possible consequence for the remaining cerrado patches could be the decrease of the woody component due to the increase of perturbations within patches, such as fires and border effect, converting the vegetation into a more open and shallow-rooted system as observed in other savanna regions of South America (Baldi et al., 2006; Thielen et al., 2008; Moreira, 2000). The replacemement of a complex deep-root wood-grass ecosystem by shallow-rooted uniform vegetation (including coffee and other crops) is likely to change the momentum and mass transfer across the landscape, leading to modifications of the hydrological cycle as well as energy and carbon balance. Thus, there are indications that the history of land use changes in Minas Gerais have affected the functioning of the ecosystems, increasing the regional effects of weather variability over landscape processes, as discussed by other authors (Jepson, 2005; Beerling & Osborne, 2006; Pinheiro & Monteiro, 2006).

Notwithstanding, the land covered by forests seems to be more conserved in the studied sites than cerrado. The forests were highly disconnected and randomly distributed in the landscapes, and were related to areas of high declivity, in general associated with conservation and protection, as on the borders of water bodies. This could be an indication that the exploitation of land resources in Minas Gerais is related to areas where the mechanization, and thus agriculture, is favored. Because the most of the studied landscapes were occupied by anthropogenic uses, perturbations able to affect agricultural ecosystems would seriously impact the regional landscape, affecting directly the socio-economic activities. However, few studies have been conducted to verify the possible implications of the effects of climatic changes over agricultural ecosystems and their implications in the landscape functioning.

In general, these results indicated that land cover structure in three sites of Minas Gerais is not a random process. In contrast, it occurs as a consequence of occupation by agriculture or intensive cattle ranching. Other possible fragmentation drivers seemed to have smaller effects. As land cover patterns changed over the studied sites in Minas Gerais in time and space in a coordinated way, we could expect parallel effects of climatic changes on ecosystems functioning and biodiversity. Therefore, actions should be implemented with the aim of managing the landscape to favor production and conservation of biodiversity based on the vulnerability and sustainability concept. The management practices should allow a balance between agriculture and conservation at different organization levels, from genes to ecosystems, which could strongly enhance the physiological plasticity of vegetation to weather variability (Pearson & Dawson, 2006; Körner & Jeltsch, 2008).

4.2 FIRE REGIME IN MINAS GERAIS

The spatial representation of the NFI indicated that fire distribution in Minas Gerais was not homogenous, but it was concentrated in some regions, with fires occurring every year in the same place. These spatial patterns of NFI distribution was probably related to land cover structure, weather characteristics and anthropogenic factors influencing the ignition processes. These factors are pointed out by some authors as the major causes defining the space fire distribution in tropical regions (Bucini & Lambin, 2002; Roman-Cuesta, 2003; Di Bella et al., 2006). When the NFI maps were overlaid on the land cover map of the north of the state, we observed that most of the fire occurred in grid cells under high anthropogenic pressure. These pixels were dominated by agricultural uses and cerrado, indicating that the fire frequency was probably related to agricultural fires, used for management practices and clearing activities, spreading to the fire-prone cerrado vegetation. Although this is an empirical observation, it corroborates with observations made by other researchers in the cerrado ecosystem (Hoffmann et al., 2003; Mistry, 2005; Di Bella et al., 2006).

The inter-annual weather variability caused by ENSO resulted in droughts and heat waves in the dry season. When we compared the fire frequency in time with the ENSO occurrence, we verified that fire incidence was correlated with ENSO events. Similar observations were made by Roman-Cuesta et al. (2003) in Mexican landscapes and by Di Bella et al. (2006) in some regions of South America. In terms of annual weather variability, we observed that fire activity resulted from a seasonal distribution of rainfall and temperature along the year, which exclusively concentrated fires in the late dry season (August to October). This period is characterized by minimum fuel moisture, minimum air humidity and increased temperatures, as discussed by some researchers (Bucinni & Lambim, 2002; Roman-Cuesta et al., 2003; Di Bella et al., 2006).

The weather variability among the regions was probably the cause of the great fire frequency observed in the north of Minas Gerais. This region showed lower rainfall values and highest temperature during the period of analysis. These weather conditions favor the fire occurrence in the semi-arid regions of Brazil, as indicated by Di Bella et al. (2006). Although further works need to be done to restrict the causes of fire frequency in each region, correlating fire frequency, land cover and weather variability, our results indicate that the regions of cerrado (north and west) could be more vulnerable to fire, because fire can spread from agricultural lands to natural vegetation patches and because the dry season is very strong in these areas.

The results of our exercise to forecast the climatic risk of fire occurrence indicated that, in general, fire frequency in Minas Gerais would tend to increase in the next years, with the current trends of weather variability. This was a simple correlation exercise between different datasets to describe fire risk as a function of weather variability, and not an elaborate model of fire occurrence. We did not considerate aspects of land cover and the feedbacks of biomass combustion. However, this is important, since the regional study of fire occurrence indicated that some differences of NFI values among the three regions could be due to the amount of fuel available to burn in each region. The feedback responses of ecosystems to weather and of biomass need to be quantified and predicted, and human-environment factors and land cover properties need to be implemented as well, to improve this approach. In tropical areas, the human-related fires can be more important than weather variability in causing fire, because human causality can be responsible for almost 90% of the ignitions in South America, as suggested (Roman-Cuesta et al., 2003; Garrigues et al., 2008), and ecosystems are more fragile and less resilient to human pressures than to natural disturbances (Thonicke et al., 2001; Roman-Cuesta et al., 2003; Bond et al., 2005; Keith et al., 2007).

However, these results provided a baseline description of the patterns of fire occurrence in Minas Gerais, suggesting strong interactions between fire occurrence and annual and inter-annual weather variability, reproducing results that have been obtained widely at more local or regional scales (Bucinni & Lambim, 2002; Roman-Cuesta et al., 2003; Mistry, 2005). Across Minas Gerais regions, agricultural activities and water deficit could be associated with more frequent fires, especially in the north of Minas Gerais. Policy approaches to fire regulation in the future should consider these interactions, adapting rules to local situations and focusing enforcement in areas with high vulnerability to fires. This would be an attempt to prevent biomass burning and avoid carbon release to the atmosphere. Furthermore, the development of regional relationships between weather variability, biomass feedbacks, anthropogenic pressures and land use structure could be the basis to improve the representations of the fire regime in landscape models as well as to perform predictions of the risk of fire occurrence related to future climate scenarios. These approaches would, consequently, benefit studies of the vulnerability to climate changes at the landscape level in Minas Gerais.

5 REFERENCES

BALDÍ, G.; GUERSCHMAN, J. P.; PARUELO, J. M. Characterizing fragmentation in temperate South America grasslands. **Agriculture, Ecosystems and Environment**, Amsterdam, v. 116, n. 3-4, p. 197-208, Sept. 2006.

BEERLING, D. J.; OSBORNE, C. P. The origin of the savanna biome. **Global Change Biology**, Oxford, v. 12, n. 11, p. 2023–2031, Nov. 2006.

BOND, W. J.; WOODWARD, F. I.; MIDGLEY, G. F. The global distribution of ecosystems in a world without fire. **New Phytologist**, Cambridge, v. 165, n. 2, p. 525–538, Feb. 2005.

BUCINNI, G.; LAMBIN, E. F. Fire impacts on vegetation in Central Africa: a remote-sensing-based statistical analysis. **Applied Geography**, Oxford, v. 22, n. 1, p. 27–48, Jan. 2002.

CERNUSAK, L. A.; HUTLEY, L. B.; BERINGER, J.; TAPPER, N. J. Stem and leaf gas exchange and their responses to fire in a north Australian tropical savanna. **Plant, Cell and Environment**, Oxford, v. 29, n. 4, p. 632–646, Apr. 2006.

DI BELLA, C. M.; JOBBÁGY, E. G.; PARUELO, J. M.; PINNOCK, S. Continental fire density patterns in South America. **Global Ecology and Biogeography**, Oxford, v. 15, n. 2, p. 192-199, Mar. 2006.

GARRIGUES, S.; ALLARD, D.; BARET, F. Modeling temporal changes in surface spatial heterogeneity over an agricultural site. **Remote Sensing of Environment**, New York, v. 112, p. 588-602, Feb. 2008.

HARGIS, C. D.; BISSONETTE, J. A.; DAVID, J. L. The behavior of landscape metrics commonly used in the study of habitat fragmentation. **Landscape Ecology**, Dordrecht, v. 13, n. 3, p. 167-186, June 1998.

HOFFMANN, W. A.; ORTHEN, B.; NASCIMENTO, P. K. V. Comparative fire ecology of tropical savanna and forest trees. **Functional Ecology**, Oxford, v. 17, n. 6, p. 720–726, Dec. 2003.

JEPSON, W. A disappearing biome? Reconsidering land-cover change in the Brazilian savanna. **The Geographical Journal**, London, v. 171, n. 2, p. 99-111, June 2005.

KEITH, D. A.; HOLMAN, L.; RODOREDA, S.; LEMMON, J.; BEDWARD, M. Plant functional types can predict decade-scale changes in fire-prone vegetation. **Journal of Ecology**, Oxford, v. 95, n. 6, p. 1324–1337, Nov. 2007.

KÖRNER, K.; JELTSCH, F. Detecting general plant functional type responses in fragmented landscapes using spatially-explicit simulations. **Ecological Modelling**, Amsterdam, v. 210, n. 3, p. 287-300, Jan. 2008.

LANGNER, A.; MIETTINEN, J.; SIEGERT, F. Land cover change 2002-2005 in Borneo and the role of fire derived from MODIS imagery. **Global Change Biology**, v. 13, p. 2329-2340, 2007.

LI, C. Estimation of fire frequency and fire cycle: a computational perspective. **Ecological Modelling**, Amsterdam, v. 154, n. 1-2, p. 103–120, Aug. 2002.

MILHÉ, N. **Contribution a l'élaboration d'indicateurs spatiaux pour le suivi des habitats naturels par utilisation d'indices de structure du paysage: application à la Grande Camargue**. 2003, 49 p. Dissertation (Structures et dynamiques spatiales/Evaluation et modélisation des territoires) – Université de Provence Aix-Marseille I, Marseille, France.

MISTRY, J. Assessing fire potential in a Brazilian savanna nature reserve. **Biotropica**, St. Louis, v. 37, n. 3, p. 439–451, Sept. 2005.

MITCHELL, T. D.; JONES, P. D. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. **International Journal of Climatology**, Sussex, v. 25, n. 6, p. 693-712, May 2005.

MOREIRA, A. G. Effects of fire protection on savanna structure in Central Brazil. **Journal of Biogeography**, Oxford, v. 27, n. 4, p. 1021–1029, July 2000.

MOUILLOT, F.; RAMBAL, S.; JOFFRE, R.; Simulating climate change impacts on fire frequency and vegetation dynamics in a Mediterranean-type ecosystem. **Global Change Biology**, Oxford, v. 8, n. 5, p. 423– 437, May 2002.

MOUILLOT, F.; FIELD, C. B. Fire history and the global carbon budget: a $1^o x 1^o$ fire history reconstruction for the 20th century. **Global Change Biology**, Oxford, v. 11, n. 3, p. 398–420, Mar. 2005.

PEARSON, R. G.; DAWSON, T. Integrating multiple modelling approaches to predict the potential impacts of climate change on species' distributions in contrasting regions: comparison and implications for policy. **Environmental Science & Policy,** Oxford, v. 9, n. 2, p. 129–147, 2006.

PEREIRA, E. B.; MARTINS, F. R.; ABREU, S. L.; COUTO, P.; STUHLMANN, R.; COLLE, S. Effects of burning of biomass on satellite estimations of solar irradiation in Brazil. **Solar Energy**, Oxford, v. 68, n. 1, p. 91–107; Jan. 2000.

PINHEIRO, M. H. O.; MONTEIRO, R. Contribution of forest species to the floristic composition of a forested savanna in Southeastern Brazil. **Brazilian Archives of Biology and Technology**, Curitiba, v. 49, n. 5, p. 763-774, Sept./Oct. 2006.

RIAÑO, D.; RUIZ, J. A. M.; ISIDORO, D.; USTIN, S. L. Global spatial patterns and temporal trends of burned area between 1981 and 2000 using NOAA-NASA Pathfinder. **Global Change Biology**, Oxford, v. 13, n. 1, p. 40-50, Jan. 2007.

ROMÁN-CUESTA, R. M.; GRACIA, M.; RETANA, J. Environmental and human factors influencing fire trends in enso and non-enso years in tropical Mexico. **Ecological Applications**, Washington, v. 13, n. 4, p. 1177–1192, Aug. 2003.

SALAS-MÉLIA, D.; CHAUVIN, F.; DÉQUÉ, M.; DOUVILLE, H.; GUÉRÉMY, J. F.; MARQUET, P.; PLANTON, S.; ROYER, J. F.; TYTECA, S. Description and validation of the CNRM-CM3 global coupled model. **Climate Dynamics**, New York, 2005.

SANTOS, A. J. B.; SILVA, G. T. D. A.; MIRANDA, H. S.; MIRANDA, A. C.; LLOYD, F. Effects of fire on surface carbon, energy and water vapour fluxes over campo sujo savanna in central Brazil. **Functional Ecology**, Oxford, v. 17, n. 6, p. 711–719, Dec. 2003.

SAUNDERS, D. A.; HOBBS, R. J.; MARGULES, C. R. Biological consequences of ecosystem fragmentation: a review. **Conservation Biology**, Cambridge, v. 5, n. 1, p. 18-32, Mar. 1991.

SOUTHWORTH, J.; MUNROE, D.; NAGENDRA, H. Land cover change and landscape fragmentation—comparing the utility of continuous and discrete analyses for a western Honduras region. **Agriculture, Ecosystems and Environment**, Amsterdam, v. 101, n. 2-3, p. 185-205, Feb. 2004.

THIELEN, D. R.; SAN JOSÉ, J. J.; MONTES, R. A.; LAIRET, R. Assessment of land use changes on woody cover and landscape fragmentation in the Orinoco savannas using fractal distributions. **Ecological Indicators**, Amsterdam, v. 8, n. 3, p. 224-238, May 2008.

THONICKE, K.; VENEVSKY, S.; SITCH, S.; CRAMER, W. The role of fire disturbance for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model. **Global Ecology & Biogeography**, Oxford, v. 10, n. 6, p. 661–677, Nov. 2001.

CHAPTER IV

Relations among leaf-to-canopy functioning, seasonality and vulnerability to global changes in the landscape of Minas Gerais

ABSTRACT

BARBOSA, João Paulo Rodrigues Alves Delfino. Relations among leaf-to-canopy functioning, seasonality and vulnerability to global changes in the landscape of Minas Gerais. In: ______. **Vulnerability of the Minas Gerais landscape to global changes:** an initial step to a bottom-up approach. 2008. Chap. 4, 193 p. Thesis (Agronomy/Plant Physiology) – Federal University of Lavras, Lavras.*

The interactions between leaf traits and ecosystem processes are an important focus for the assessment of the impacts of global changes over landscape properties due to the implications in the development of landscape simulation models and on scaling exercises. The emphasis of this research is to present some aspects of functioning at the leaf and ecosystem levels and insights into the links among the leaf traits, vegetation structure, and ecosystem functioning of coffee, eucalypt and cerrado in the landscape of Minas Gerais, related to the seasonality. The ecosystem functioning was analyzed by remotely sensed parameters from MODIS (GPP, NDVI and LSWI), fitted by TIMESAT 2.3 to verify the seasonality patterns of functioning. The leaf physiology and vegetation structure was assessed by a literature survey. Our results indicated that the functioning of the ecosystems in the landscape of Minas Gerais was strongly affected by the seasonality, decreasing the functioning processes in the dry season. Seasonal changes in soil-plant (measured by maximum leaf water potential) and atmospheric water status (measured by the leaf-to-air vapor pressure deficit) had significant impacts on seasonal patterns of stomatal conductance, transpiration and photosynthesis in all examined ecosystems. These patterns of leaf functioning were observed in the correlations with remotely sensed indices. This way, the seasonality in the water availability was the main factor controlling the vegetation activity on the leaf and the landscape level. Plants of cerrado and eucalypt were less sensitive to seasonal variability, probably due to the root system depth, but coffee plants had their functioning strongly affected by the reduction in the availability of water in one season of the year. Such diagnostic study would be helpful in the assessment of the vulnerability of the landscape of Minas Gerais to the global changes, because it was possible to define threshold values of key leaf traits influencing the capacity of carbon assimilation and water use by the ecosystems.

Key-words: leaf traits, remote sensing, scaling changes, cerrado, eucalypt, coffee.

---

* Guidance Committee: Prof. Dr. Angela Maria Soares (Adviser), Dr. Serge Rambal - CEFE/CNRS (Co-adviser).

RESUMO

BARBOSA, João Paulo Rodrigues Alves Delfino. Relações entre funcionamento da folha e do ecossistema, sazonalidade e vulnerabilidade às mudanças globais na paisagem de Minas Gerais In:______. **Vulnerabilidade da paisagem de Minas Gerais às mudanças globais:** um passo inicial para uma abordagem tipo *bottom-up*. 2008. Cap. 4, 193 p. Tese (Agronomia / Fisiologia Vegetal) – Universidade Federal de Lavras, Lavras.*

As interações entre características foliares e processos dos ecossistemas são importantes para o desenvolvimento de modelos de simulação da paisagem e para mudança de escala, sendo fundamental para estudar os impactos das mudanças globais nas propriedades da paisagem. O objetivo desse trabalho foi apresentar aspectos e acessar conexões entre o funcionamento da folha e do ecossistema, a estrutura da vegetação e a sazonalidade em cafezal, eucaliptal e cerrado, na paisagem de Minas Gerais. O funcionamento dos ecossistemas foi avaliado através de parâmetros de sensoriamento remoto obtidos por imagens MODIS (GPP, NDVI e LSWI), e ajustados pelo software TIMESAT 2.3 para verificar padrões sazonais de funcionamento. A fisiologia foliar e a estrutura da vegetação foram obtidas de uma revisão de literatura. Os resultados indicaram que o funcionamento dos ecossistemas foi grandemente influenciado pela sazonalidade, com depressão dos processos de trocas gasosas na estação seca. Padrões sazonais no status hídrico do sistema solo-planta (medido pelo potencial hídrico máximo) e na atmosfera (medido pelo déficit de pressão de vapor entre folha-ar) apresentou impactos significantes nos padrões sazonais de condutância estomática, transpiração e taxa fotossintética de todas as espécies estudadas. Tais padrões também foram observados nos índices de sensoriamento remoto, indicando que a disponibilidade hídrica foi o principal fator de controle do funcionamento da vegetação, da folha à paisagem. Plantas de cerrado e eucalipto foram menos sensíveis à variabilidade sazonal na disponibilidade hídrica, provavelmente devido ao seu sistema radicular mais profundo; no entanto, o cafeeiro foi fortemente influenciado pela redução da disponibilidade de água em uma época do ano. Esses resultados poderão ser utilizados para acessar a vulnerabilidade da paisagem de Minas Gerais às mudanças globais, uma vez que análises desse tipo permitem conhecer valores limites das principais características foliares capazes de influenciar a capacidade de assimilação de carbono e do uso da água nos ecossistemas.

Palavras-chave: características foliares, sensoriamento remoto, mudanças de escala, cerrado, eucalipto, cafeeiro.

---

* Comitê Orientador: Prof[a]. Dr[a]. Angela Maria Soares (Orientadora), Dr. Serge Rambal - DREAM/CEFE/CNRS (Co-orientador).

1 INTRODUCTION

It has been recognized that dominant leaf traits strongly influence canopy functioning. The ecophysiological studies on the links between leaf traits and canopy physiology are highly relevant to ecosystem modeling because of the concerns about the effects of abiotic stress on the functioning of vegetation (Lavorel et al., 1999; Díaz et al., 1999; Wright et al., 2005a). In general, the simulation models are square-grid representations, in a way that to each cell is assigned a set of typical properties, often including leaf traits such as specific leaf area, net carbon assimilation and water use efficiency (Wright et al., 2005b). Due to this spatially-explicit implication, there is the necessity of scaling physiological processes in space.

A good way to observe the correlations and to develop scaling methods of plant physiology with whole canopy functioning is by the association of remote sensing of functional indices, (such as the normalized difference of vegetation index NDVI), and leaf traits. By remote sensing techniques, carbon flux, surface water status, intercepted radiation and leaf area index can be used in the spatialization and comprehension of the effects of seasonality on ecosystem functioning. Based on this, the use of remote sensing indices and leaf traits can be employed to detect the dynamic interactions between the physiological and biophysical processes that happen on different space-time scales related to seasonality (Potter et al., 1998; Ichii et al., 2007; Grace et al., 2007).

The development of these relationships can lead to discussions about the potential effects of the climatic changes on the vegetation, since the up and downscaling of physiological processes are facilitated (Hurtt et al., 1998) and threshold values of key leaf traits affecting ecosystems functioning are defined (Rambal et al., 2003). This can be particularly important in the studies of climatic impacts on the leaf level, because the scenarios of future climate are integrated on large scales. However, these responses are particular to each ecosystem being both, site and species-specific (Kosugi et al., 2006). Therefore, the representations of the state of leaf-to-canopy functioning can be very particular, making it vital for improved descriptions and simulations of landscape functioning under weather variability (Saleska et al., 2003).

The landscape of the state of Minas Gerais, southeast Brazil, has to cope with an annual and inter-annual seasonality of rainfall and temperature. We studied leaf traits and canopy properties of three ecosystems in three sites of Minas Gerais considering this seasonality and its sapatial variability. Our objective was to provide a first-step toward the understanding of the relationships of the leaf-to-canopy functioning during the wet and dry seasons, verifying the controls of weather variability in leaf traits and canopy functioning in coffee and eucalypt plantations and in cerrado ecosystems in the landscape of Minas Gerais.

2 MATERIAL AND METHODS

2.1 STUDY SITES

Three sites were selected in the state of Minas Gerais, southeast Brazil, for the remote sensing of vegetation indices. An area was chosen in the north of the state (15°20’ to 17°10’S, 42°20’ to 45°05’W and average altitude of 466 m), where cerrado and *Eucalyptus* sp. plantations were the target ecosystems. A second site was selected in the south of Minas Gerais (21°30’ to 22°00’S, 45°20’ to 46°05’W and altitude of 1215 m), with *Coffea arabica* L. plantations. The last site was selected in the west of Minas Gerais (18°30’ to 19°00’S, 46°10’ to 46°50’W, and altitude 873 m) with coffee plantations and cerrado vegetation (Figure 1A). The three study sites laid over dystrophic, deep soils with medium (approximately equal parts of sand, silt and clay) to clayey (between 35 and 60% clay and equal parts of silt and sand) texture. The declivity of the northern site ranged between 0% and 45%, between 13% to over 70% in the south and from 0% to 45% in the west of Minas.

Thematic maps of the study sites were used for the plot selection. The land cover maps were generated from Landsat TM images from 2002 (west, spatial resolution of 30m), from 2005 (south, spatial resolution of 10m) and from 2003 (north, spatial resolution of 30m). The maps from west and southern sites were obtained from the Laboratório de Geoprocessamento da Empresa de Pesquisa Agropecuária de Minas Gerais (GEOSOLOS-EPAMIG http://www.epamig.br/Geosolos-EPAMIG/), and the northern vegetation map from the Laboratório de Estudos em Manejo Florestal-Universidade Federal de Lavras (LEMAF-UFLA http://www.dcf.ufla.br/LEMAF-UFLA/). We selected 5 plots of each studied ecosystems at the respective sites, totaling 25 plots. Each plot was composed by three target sub-plots of 1km x 1km, surrounded by the same land cover class on all the sides (border pixels), as exemplified in figure 1B.

The annual and seasonal average values of mean air temperature and precipitation, from 2000 to 2006 in the south, west and north of Minas Gerais is shown in table 1. The south was colder than the other two regions. The north of Minas Gerais was the warmest region and the west showed intermediate temperature values. The precipitation in the dry season was similar in the three regions. The north region showed lower averages of annual and wet season precipitation than the south and west.

2.2 REMOTE SENSING OF CANOPY FUNCTIONING AND SEASONALITY

The vegetation indices were extracted from images of the **M**oderate **R**esolution **I**maging **S**pectroradiometer (MODIS) onboard the Terra satellite, one of the optical sensors in the **N**ational **A**eronautics and **S**pace **A**dministration (NASA) **E**arth **O**bserving **S**ystem (EOS). In this study, we used the eight day composite (46 observations ≈1 year) estimates from 2002 to 2006, of the NDVI (normalized difference of vegetation index, spatial resolution of 0.5km), LSWI (land surface water index, spatial resolution of 0.5km) and GPP (gross primary production, spatial resolution of 1km). For each 8-day composite, NDVI and LSWI were calculated using surface reflectance values from the red (ρ_R, 620-670nm), near-infrared (ρ_{NIR}, 841–875 nm) and shortwave infrared (ρ_{SWIR}, 1628–1652 nm) bands, as demonstrated byXiao et al. (2005).

$$\mathrm{NDVI} = (\rho_{NIR} - \rho_R) \times (\rho_{NIR} + \rho_R)^{-1} \quad (1)$$

$$\mathrm{LSWI} = (\rho_{NIR} - \rho_{SWIR}) \times (\rho_{NIR} + \rho_{SWIR})^{-1} \quad (2)$$

Table 1 – Annual and seasonal average values of precipitation and mean air temperatures observed from 2000 to 2006 and normal values from 1961 to 1990 in the north, south and west regions of Minas Gerais.

	North		South		West	
	00-06*	61-90**	00-06	61-90	00-06	61-90
	Precipitation (mm)					
Annual	770±85	981±74	1245±92	1561±95	1354±51	1582±98
Wet season	605±56	874±48	1042±69	1279±58	1131.6±61	1325±51
Dry season	173±29	107±15	202±45	282±21	223±47	266±33
	Mean temperature (°C)					
Annual	25.0±0.5	23.5±0.5	20.1±0.7	18.8±0.8	21.4±0.4	21.3±0.5
Wet season	25.8±0.4	24.8±0.3	22.0±0.2	21.4±0.2	22.6±0.2	22.9±0.3
Dry season	23.6±0.6	22.2±0.4	15.6±0.8	16.3±1.0	20.2±0.4	19.8±0.4

* - Averages from 3 automatic weather stations in the south (Lavras, Machado and Itajubá), and 2 in the north (Januária and Salinas) and west (Araxá and Patrocínio). Source: Instituto Nacional de Meteorologia (INMET) (http://www.inmet.gov.br/html/rede_obs.php) and Centro de Previsão do Tempo e Estudos Climáticos – Instituto Nacional de Pesquisas espaciais CPTEC-INPE (http://satelite.cptec.inpe.br/PCD/pcd.jsp?uf=12).
** - Averaged from north (Montes Claros and Araçuaí); south (Machado and Lavras); west (Araxá and Uberaba). Source: Brasil (1992).

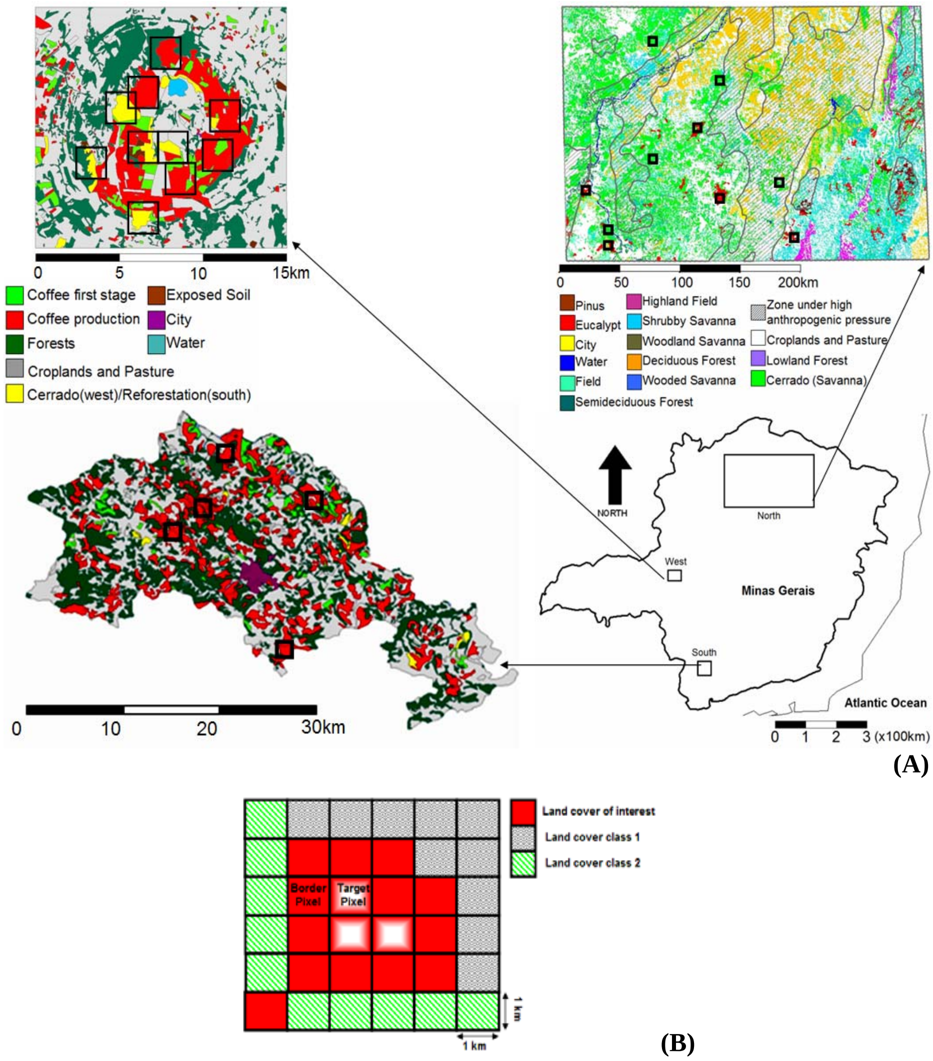

Figure 1 – (A) Study sites in Minas Gerais (north, west and south). The black squares in the land cover maps indicate the location of the plots used in the analysis of remotely sensed indices. (B) A scheme of the plots: the target pixels (red-white) were surrounded by border pixels (red) of the same land cover class.

The GPP was estimated using the PAR and Fapar MODIS products, as described by Miglietta et al. (2007):

$$GPP = \varepsilon \times Fapar \times PAR \qquad (3)$$

where PAR is the incident photosynthetically active radiation (MJ m^{-2}) in the 8-day composite, Fapar is the fraction of absorbed PAR by the vegetation canopy and ε is the light use efficiency for fixed carbon (g C MJ^{-1} of PAR), that is calculated as:

$$\varepsilon = \varepsilon_{max} \times f_1(T_{min}) \times f_2(VPD) \qquad (4)$$

where ε_{max} is the vegetation specific maximum conversion efficiency. The functions $f1$ and $f2$ (between 0 and 1) describe the influence of meteorological conditions on ε with T_{min} being the daily minimum air temperature and VPD the daytime average vapor pressure deficit.

The MODIS imagery was treated with a window size of two time steps to remove occasional sudden spikes likely caused by atmospheric effects or non vegetated areas. This treatment was performed by the TIMESAT 2.3 (Jönsson & Eklundh, 2004) software. The data generated by this fitting process was used for the analysis of seasonality, according to the methodology showed by Jönsson & Eklundh (2002).The duration of the seasons was defined as the time from which the value had increased by 10% of the distance between the minimum level and the peak. The amplitude of the season was obtained as the difference between the peak and the average of the left and right minimum values (Figure 2).

The Global Inventory Modeling and Mapping Studies (GIMMS) (Tucker et al., 2004) product was used to analyze NDVI from 1981 to 2003 in 3 pixels dominated by the target ecosystem in each region, for each ecosystem. This time-series was used to observe long-term patterns of NDVI related to climate variability caused by ENSO (El Niño southern oscillation) episodes.

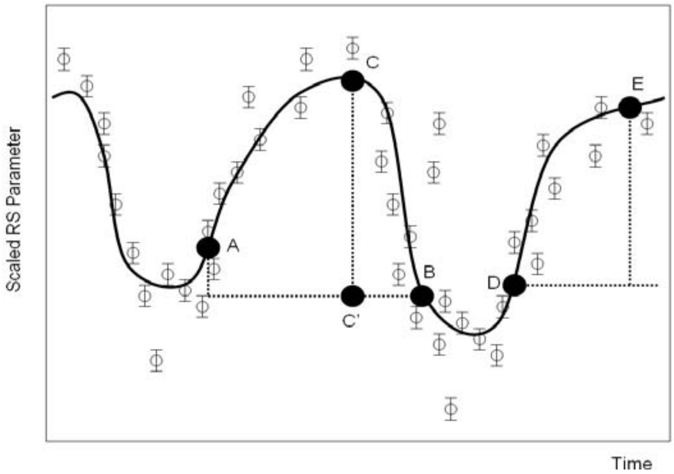

Figure 2 – The approach used to extract seasonality parameters in the TIMESAT time-series: open symbols with error bars indicate the values from MODIS; the solid line is the data fitted by TIMESAT. Black dots represent: (A and D) beginning of season, (B) end of season, (C and E) peak, (C') average value between (A) and (B), (C-C') amplitude, (A-C') length of high vegetation activity season, (C'-B) length of the low vegetation activity season. Adapted from Jönsson & Eklundh (2004).

2.3 LEAF TRAITS AND ECOSYSTEM STRUCTURE: A LITERATURE SURVEY

To build a database able to supply information about leaf traits and ecosystem structure of coffee, cerrado and eucalypt, we used a literature survey as data source. The *ISI Web of Science*, *Google Scholar*, *Sciencedirect* and the central library of the Universidade Federal de Lavras (UFLA) were the main databases searched for comparative studies reporting the ecophysiological or structural information of the three target ecosystems. The keywords used in searches were various combinations of 'photosynthetic rate', 'leaf water potential', 'SLA', 'biomass', 'root system depth' together with 'coffee', '*Coffea arabica*', 'cerrado', 'eucalypt' or '*Eucalyptus*' and 'Minas Gerais'. No restriction was made to date of publication. Only the data under common conditions (i.e. standard nutrition, light, and water) in field or greenhouse were used in our approach. The eucalypt species considered were *E. grandis, E. regnans, E. urophylla, E. saligna, E. camadulensis* and *E. globulus*. For coffee, we only considered *Coffea arabica* information. For cerrado, we used four plant functional types: deciduous, semideciduous, brevideciduous and evergreen species (Scholz et al., 2007).

We selected 7 leaf traits: net photosynthetic rate (A, μmol m^{-2} s^{-1}), transpiration rate (E, mmol m^{-2} s^{-1}), specific leaf area (SLA, m^2 kg^{-1}), minimum and maximum leaf water potential (Ψmin and Ψmax, MPa), stomatal conductance (gs, mol m^{-2} s^{-1}), sub-stomatal to atmosphere carbon rate (Ci Ca^{-1}, ppm ppm^{-1}). We derived the instantaneous water use efficiency (WUE, mmol CO_2 [mmol $H_2O]^{-1}$) from the ratio between A and E. The structural information was composed of the maximum root depth (RD, m), average canopy height (CH, m), density of stems (D, stems.ha^{-1}), leaf area index (LAI, m^2 m^{-2}). Totally, we consulted 71 references. Most of this material was about cerrado (40%), the information about eucalypt was restricted to 25% of our literature survey, and 35% was used to assess information about coffee (Table 2).

2.4 DATA ANALYSIS

Averages of the raw data for the leaf traits and remotely sensed parameters were analyzed by standard analysis of variance (ANOVA). For remotely sensed data (amplitude and length of seasons, seasonal values of the indices and ENSO and non-ENSO years / seasons of NDVI GIMMS), each plot was considered one replicate for the calculation of the standard error. The averages were compared by the Tukey test at α = 5%. The relationship of leaf traits and remotely sensed indices was verified by regression analysis, using the least-squares method and the *t-test* at α = 1%. We correlated the values of the 10th, 25th, 75th, 90th percentiles of the normal distribution and the average and median of each variable in the dry and in the wet seasons.

Table 2 – The literature survey of leaf traits and structural characteristics of the studied ecosystems (SE): coffee (Cf), eucalypt (Ec) and cerrado (Cd). Leaf traits were: net photosynthetic rate (A, µmol m^{-2} s^{-1}), transpiration rate (E, mmol m^{-2} s^{-1}), specific leaf area (SLA, m^2 kg^{-1}), minimum and maximum leaf water potential (Ψmin and Ψmax, MPa), stomatal conductance (gs, mol m^{-2} s^{-1}), sub-stomatal to atmosphere carbon rate (Ci Ca^{-1}, ppm ppm^{-1}) and water use efficiency (WUE, µmol $CO_2[mmolH_2O]^{-1}$). Structural characteristics were: maximum root depth (RD, m), average canopy height (CH, m), density of stems (D, $stems.ha^{-1}$) and leaf area index (LAI, m^2 m^{-2}).

Reference	SE	Season	Leaf traits								Structural characteristics			
			A	E	gs	SLA	Ψmax	Ψmin	$CiCa^{-1}$	WUE	RD	CH	D	LAI
Almeida & Soares, 2003	Ec	Wet			0.8±0.2		-0.5±0.1				2.5	7		3.0±0.6
		Dry			0.4±0.1		-1.2±0.1							2.0±0.5
Amaral et al., 2006	Cf	Wet											6600	
		Dry												
Barbosa, 2005	Cf	Wet	5.1±0.3	1.2±0.2	0.3±0.1	10.1±1.5	-0.3±0.1	-1.6±0.8	0.7±0.2	4.2±0.4		1.4±0.4	2800	
		Dry	3.7±0.2	0.7±0.2	0.07±0.03	8.9±0.8	-1.8±0.2	-2.7±0.7	0.4±0.1	5.4±0.5				
Barros et al., 1997	Cf	Wet			0.12±0.2		-0.2±0.1	-0.8±0.3				2.5	6000	
		Dry			0.06±0.03		-0.3±0.2	-1.1±0.2						
Barton & Montagu, 2006	Ec	Wet										7.5±0.6	1667±333	
		Dry												
Batalha et al., 2001	Cd	Wet											17175±3719	
		Dry												
Brigatti et al., 1980	Ec	Wet										13.7±1.2		
		Dry												
Bucci et al., 2003	Cd	Wet												
		Dry		3.3±0.6			-0.4±0.1	-1.5±0.1						

continue...

Table 2 – Continuation...

Bucci et al., 2004a	Cd	Wet										3.1±0.2		
		Dry		3.2±0.5	0.19±0.03	5.6±2.2		-1.5±0.3						
Bucci et al., 2004b	Cd	Wet										2.4±0.2		
		Dry			0.09±0.02		-0.5±0.3	-1.6±0.2						
Bucci et al., 2005	Cd	Wet		3.7±0.2	0.5±0.2		-0.25±0.1	-1.3±0.3				3.5±1.7		
		Dry		4.2±0.1	0.15±0.07		-0.8±0.1	-1.7±0.2						
Bucci et al., 2006	Cd	Wet			0.17±0.2			-1.3±0.3						
		Dry												
Cai et al., 2005	Cf	Wet	6.5±0.3	1.7±0.3	0.2±0.1									
		Dry	1.3±0.1	0.7±0.1	0.05±0.04									
Carr, 2001	Cf	Wet					-1.0±0.5	-2.8±0.3			1.8±0.6		1500-6000	4.5±3.1
		Dry												
Carvalho et al., 2001	Cf	Wet	2.3	1.39	0.09									
		Dry												
Castro & Kauffman, 1998	Cd	Wet										2.5±0.1	1065±110	
		Dry												
Damascos et al., 2005	Cd	Wet	6.4±0.8	2.25±0.2	0.22±0.14									
		Dry												
Da Matta, 1995	Cf	Wet	4.2±0.6		0.05±0.01		-0.13±0.03	-0.4±0.1						
		Dry	1.3±0.1		0.01±0.00		-1.1±0.2	-1.8±0.8						
Da Matta et al., 1997a	Cf	Wet	3.0±0.6	1.2±0.3	0.04±0.01		-0.2			2.4±0.2				
		Dry	0.3±0.2	0.4±0.1	0.01±0.00		-2.7			1.0±0.5				
Da Matta et al., 1997b	Cf	Wet												
		Dry												
Da Matta & Maestri, 1997	Cf	Wet	2.8±0.6		0.04±0.01									
		Dry	0.2±0.3		0.01±0.00									
Dias et al., 2007	Cf	Wet	7.1±0.4	1.4±0.2	0.10±0.08	15.4±0.5	-0.13±0.02	-0.8±0.05	0.62±0.03	5.4±0.6				
		Dry	4.7±0.3	0.80±0.08	0.05±0.02	14.2±0.6	-1.5±0.2	-2.2±0.8	0.55±0.03	5.8±0.5				

continue…

Table 2 – Continuation…

Fahl et al., 1994	Cf	Wet	6.7±1.3		0.06±0.03									
		Dry												
Fahl et al., 2001	Cf	Wet	3.0±0.4		0.7±0.05							1.55±0.12		
		Dry			0.06±0.01									
Franco & Luttge, 2002	Cd	Wet	7.8±2.3	3.2±2.4	0.18±0.05									
		Dry												
Franco et al., 2005	Cd	Wet	12.2±1.9		0.18±0.07	6.9±2.5	-0.22±0.03	-1.0±0.6	0.77±0.02					
		Dry	8.9±0.7		0.11±0.03		-0.4±0.1	-1.7±0.5	0.73±0.04					
Freitas et al., 2003	Cf	Wet	0.9±0.2	0.9±02	0.01±0.01									
		Dry												
Gómez et al., 2005	Cf	Wet	8±0.7	1.3±0.2	0.08±0.04									5.3
		Dry												
Grace et al., 2006	Cd	Wet												
		Dry												
Hoffmann et al., 2005a	Cd	Wet				7.2±0.9								
		Dry												
Hoffmann et al., 2005b	Cd	Wet												1.2±0.1
		Dry												0.9±0.1
Inoue & Ribeiro, 1988	Ec	Wet		1.3±0.2						3.67±0.02		12,3±0.7		
		Dry												
Jackson et al., 1999	Cd	Wet										3.8±0.8		
		Dry						-1.7±0.8						
Konrad et al., 2005	Cf	Wet	6.8±2.3	2.8±1.1	0.11±0.07					4.2±0.8				
		Dry												
Labouriau, 1963	Cd	Wet									8.0	6.0±2.4	1067±124	
		Dry												
Leite et al., 2006	Cd	Wet												
		Dry												

continue...

Table 2 – Continuation...

Leles et al., 2001	Ec	Wet										16.0±2.4	1390±250	
		Dry												
Lemos-Filho, 2000	Cd	Wet			0.34±0.12									
		Dry			0.09±0.03									
Lima et al., 2003	Ec	Wet	12.5±2.0		0.47±0.03					3.1±0.50				
		Dry	5.7±2.5		0.2±0.05					1.25±0.75				
Martins et al., 2004	Ec	Wet											1667	
		Dry												
Mateus et al., 2006	Ec	Wet												
		Dry												
Meinzer et al., 1990	Cf	Wet	6.8±0.3		0.1±0.02		-0.14±0.05	-1.02±0.06						
		Dry	4.5±0.8		0.05±0.03		-0.7±0.06	-1.7±0.9						
Meinzer et al., 1999	Cd	Wet		2.3±0.7			-0.25±0.08	-1.5±0.3				3.0±1.5		
		Dry		1.2±0.6	0.16±0.13		-0.45±0.1	-1.8±0.2						
Mielke, 1999	Ec	Wet	13.8±2.3	3.9±1.1	0.6±0.1	7.3±0.3	-0.4±0.1	-1.2±0.1	0.7±0.0	3.1±0.3				
		Dry	6.1±0.9	2.2±0.6	0.2±0.1	6.2±0.4	-0.9±0.2	-1.5±0.2	0.6±0.0	2.8±0.3				
Miranda et al., 1997	Cd	Wet												0.9
		Dry												0.7
Morais et al., 2003	Cf	Wet	6.1±1.3	0.9±0.5		13.0±0.6						1.04±0.47	5555	
		Dry	2.3±0.6	0.43±0.1		11.0±1.2								
Nascimento et al., 2006	Cf	Wet	4.1	1.4	0.45								3333	
		Dry												
Naves-Barbieiro et al., 2000	Cd	Wet										2.8±1.3		
		Dry			0.12±0.05		-0.48±0.14	-2.15±0.3						
Oliveira, 2003	Cf	Wet	6.13±0.72	0.85±0.16	0.09±0.02	9.31±1.03	-0.22±0.06	-1.14±0.15	0.50±0.03	4.73±0.52				
		Dry	2.10±0.39	0.75±0.14	0.03±0.01	10.40±0.54	-0.98±0.24	-2.45±0.29	0.79±0.05	3.55±0.69				
Oliveira et al., 2005	Cd	Wet									7.0			
		Dry												

continue...

Table 2 – Continuation...

Oliveira et al., 2006	Cf	Wet	7.40±0.51		0.11±0.01		-0.28±0.05	-1.31±0.13				6667
		Dry	2.74±0.10		0.05±0.00		-1.33±0.24	-2.18±0.21				
Paula, 2002	Cd	Wet	11.0±2.6		0.5±0.3	6.8±0.8						
		Dry	9.3±3.7		0.2±0.1	6.5±1.7						
Pereira, 2006	Ec	Wet	18.0±2.4	2.4±0.4	0.2±0.1	7.0±1.0	-0.5±0.1	-1.1±0.2	0.7±0.1	3.2±0.4		
		Dry	8.3±1.6	1.6±0.4	0.08±0.02	5.9±0.7	-1.5±0.1	-2.2±0.2	0.6±0.1	2.6±0.2		
Prado & Morais, 1997	Cd	Wet	10.7±1.7			6.8±2.3	-1.6±0.07					
		Dry										
Prado et al., 2004	Cd	Wet	10.3±2.1	5.0±0.96	0.58±0.28		-0.08±0.03	-1.23±0.47	0.71±0.03	2.1±0.57		
		Dry	6.7±3.0	3.4±1.0	0.13±0.08		-0.35±0.21	-1.18±0.50	0.58±0.12	2.0±0.76		
Rocha et al., 2002	Cd	Wet										
		Dry										
Ronquim et al., 2003	Cd	Wet	14.5±1.2									
		Dry										
Ronquim et al., 2006	Cf	Wet	9.1±0.6	1.3±0.5	0.04±0.02		-0.25±0.05	-1.3±0.2	0.6±0.1	2.3±0.4		2860
		Dry										
Scholz et al., 2007	Cd	Wet									4.0±1.3	
		Dry			0.23±0.04		-0.5±0.3	-1.9±0.5				
Silva, 1997	Ec	Wet	20.0±1.6	3.1±0.6	0.7±0.1		-0.3±0.0	-1.2±0.1	0.8±0.1	2.6±0.3		
		Dry	8.1±1.1	2.8±0.5	0.1±0.05		-0.9±0.1	-2.5±0.5	0.7±0.1	1.9±0.2		
Silva, 2002	Cf	Wet	5.74±0.67	1.35±0.26	0.08±0.02	8.7±1.3	-0.21±0.05			3.96±0.50		
		Dry	2.92±0.62	0.75±0.14	0.05±0.01	7.4±0.8	-1.01±0.30			3.55±0.69		
Silva et al., 2004	Cf	Wet	10.3±1.3		0.09±0.02				0.8±0.06			2222
		Dry	2.7±0.6		0.05±0.01				0.4±0.03			
Silva, 2005	Cf	Wet		0.90±0.17	0.09±0.02		-0.20±0.05	-1.06±0.14				
		Dry		0.75±0.13	0.03±0.01		-1.00±0.26	-2.46±0.25				

continue...

Table 2 – Continuation...

Stape 1990	Ec	Wet											1667	
		Dry												
Stape et al., 2004a	Ec	Wet									5.0	14.4±1.4		
		Dry												
Stape et al., 2004b	Ec	Wet									6.5	15.0	1111	
		Dry												
Tatagiba et al., 2007	Ec	Wet	20.5±0.5	7.4±0.3	0.5±0.1		-1.4±0.1			2.8±0.2				
		Dry	14.7±2.7	4.2±0.9	0.2±0.5		-4.2±0.3			3.5±0.5				
Vourlitis et al., 2001	Cd	Wet												
		Dry												
Xavier et al., 2002	Ec	Wet									4.7			2.9±0.5
		Dry												
Whitford et al., 1995	Ec	Wet									6.0			1.1±0.1
		Dry												
Whitehead & Beadle, 2004	Ec	Wet	23.0±3.7		0.6±0.1	7.6±0.6								4.9±0.5
		Dry	16.2±1.8		0.25±0.05	5.4±0.9								2.5±0.3

3 RESULTS

3.1 REMOTELY SENSED INDICES

Our results demonstrated greater variability between data extracted directly from MODIS and data fitted by TIMESAT 2.3 to NDVI (R^2 = 0.68, Figure 3) than to LSWI (R^2 = 0.98, Figure 4) and GPP (R^2 = 0.84, Figure 5). The evaluated ecosystems, at the respective study sites showed minimal NDVI, LSWI and GPP values in the dry season (May to August) and maximal values in the wet season (December-March) (Figure 6). The values of NDVI and LSWI, observed in the wet season, were, in general, higher in the ecosystems in the west and south of Minas Gerais (Figures 6A, B). In the dry season, eucalypt plantations showed the highest values of LSWI, whereas cerrado, in the north of Minas Gerais, the lowest. The cerrado in the west of Minas Gerais showed the lowest values of NDVI in the dry season. For GPP, eucalypt showed the highest values in the wet season (Figure 6C). In the dry season the values were still higher, but similar with the values observed for coffee in the south.

In general, there were no differences in amplitudes of LSWI between the cerrado ecosystems and coffee plantations, at different sites (Figure 6D). However, we observed that, in general, the amplitudes for coffee were higher than those of cerrado. The amplitudes of LSWI and NDVI observed in the plots of eucalypt were the lowest (Figures 6D, E). The NDVI amplitudes in the west of Minas Gerais were similar for coffee and cerrado. The coffee in the south showed similar amplitude to the cerrado in the north of Minas Gerais, whereas those values were smaller than the ones observed for coffee in the west region. The NDVI amplitudes observed for eucalypt were the smallest.The length of both seasons observed for LSWI and for NDVI in the different study sites showed similar values along the analysis period (Figures 7 A, B, C, D).

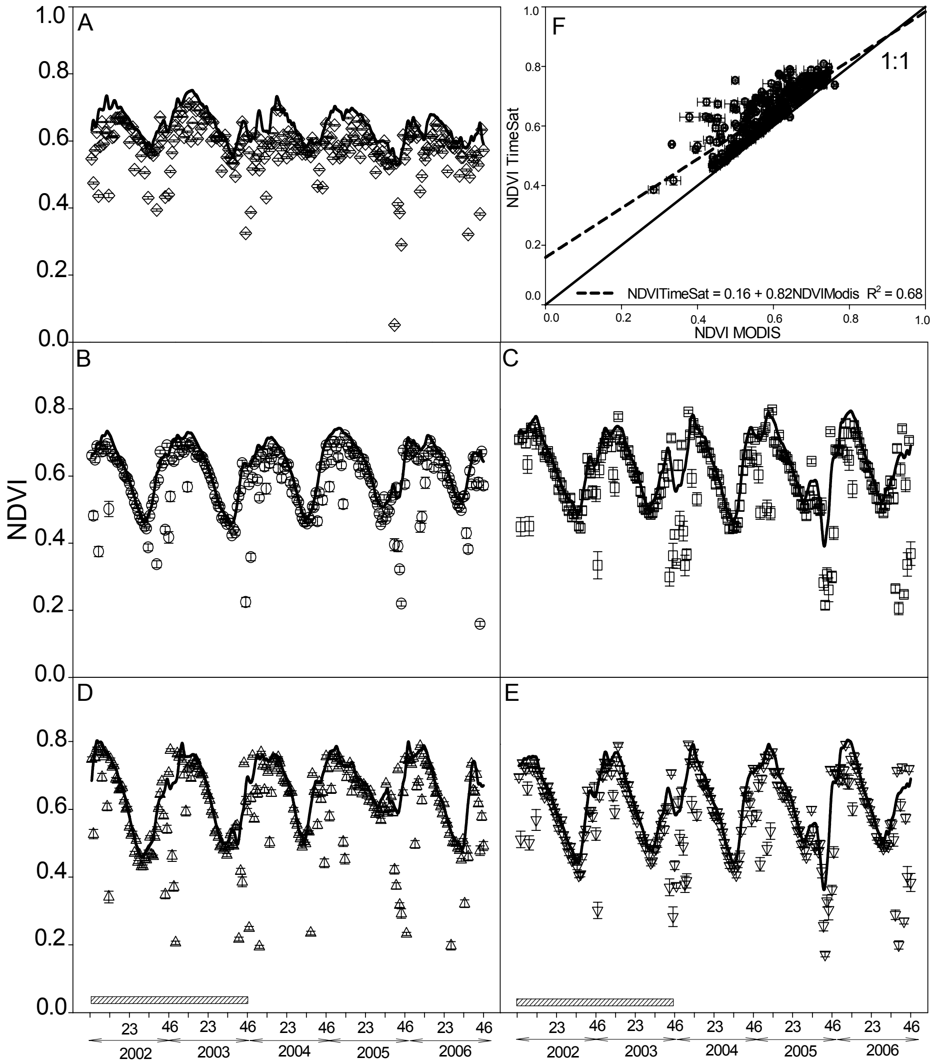

Figure 3 – NDVI MODIS (symbols) and NDVI TIMESAT 2.3 (solid lines) from 2002 to 2006 in 8 day composite, for (A) eucalypt plantations (◇) in the north of Minas Gerais, cerrado in the north (B) (O) and west (C) (□) of Minas Gerais, coffee plantation in the south (D) (△) and west (E) (▽) of Minas Gerais. Error bars represent the standard error of 5 observations. Horizontal bar on x axis indicate the ENSO event during the sample period. (F) - the regression of NDVI TimeSat in relation to NDVI Modis was calculated on a monthly basis (32 days).

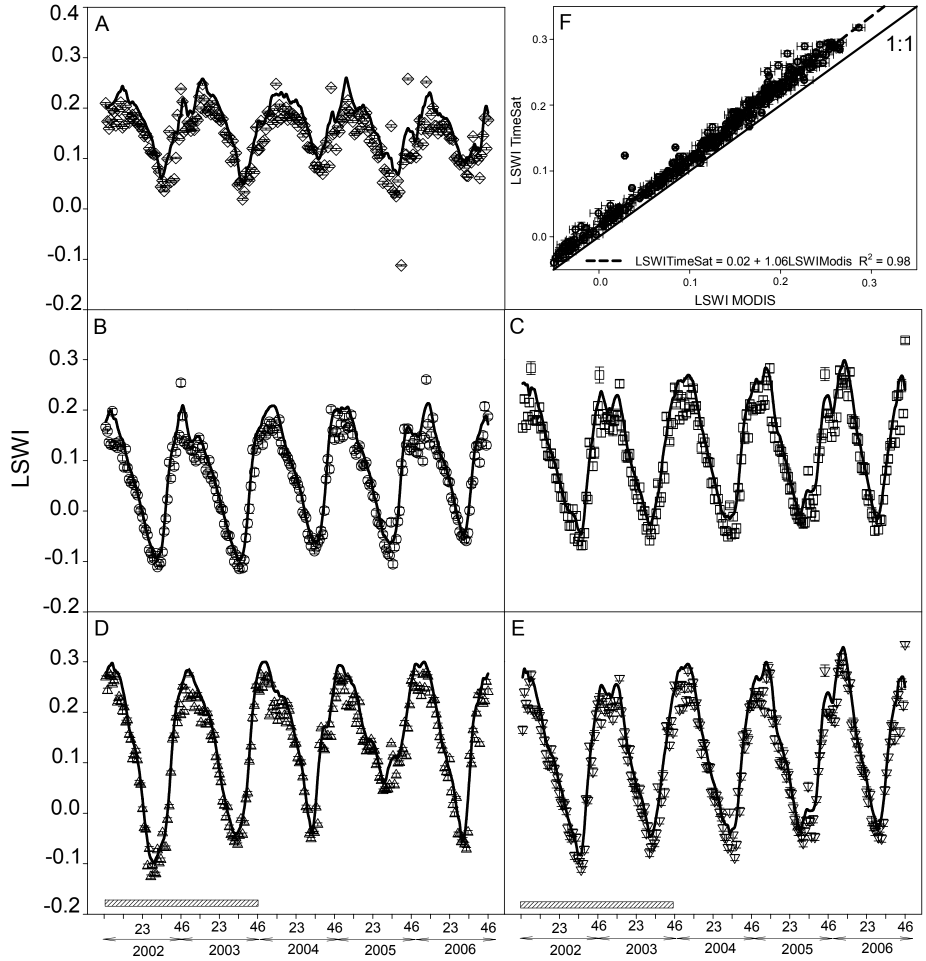

Figure 4 – LSWI MODIS (symbols) and LSWI TIMESAT 2.3 (solid lines) from 2002 to 2006 in 8 day composite, for (A) eucalypt plantations (◇) in the north of Minas Gerais, cerrado in the north (B) (O) and west (C) (□) of Minas Gerais, coffee plantation in the south (D) (△) and west (E) (▽) of Minas Gerais. Error bars represent the standard error of 5 observations. Horizontal bar on x axis indicate the ENSO event during the sample period. (F) - the regression of LSWI TimeSat in relation to LSWI Modis was calculated on a monthly basis (32 days).

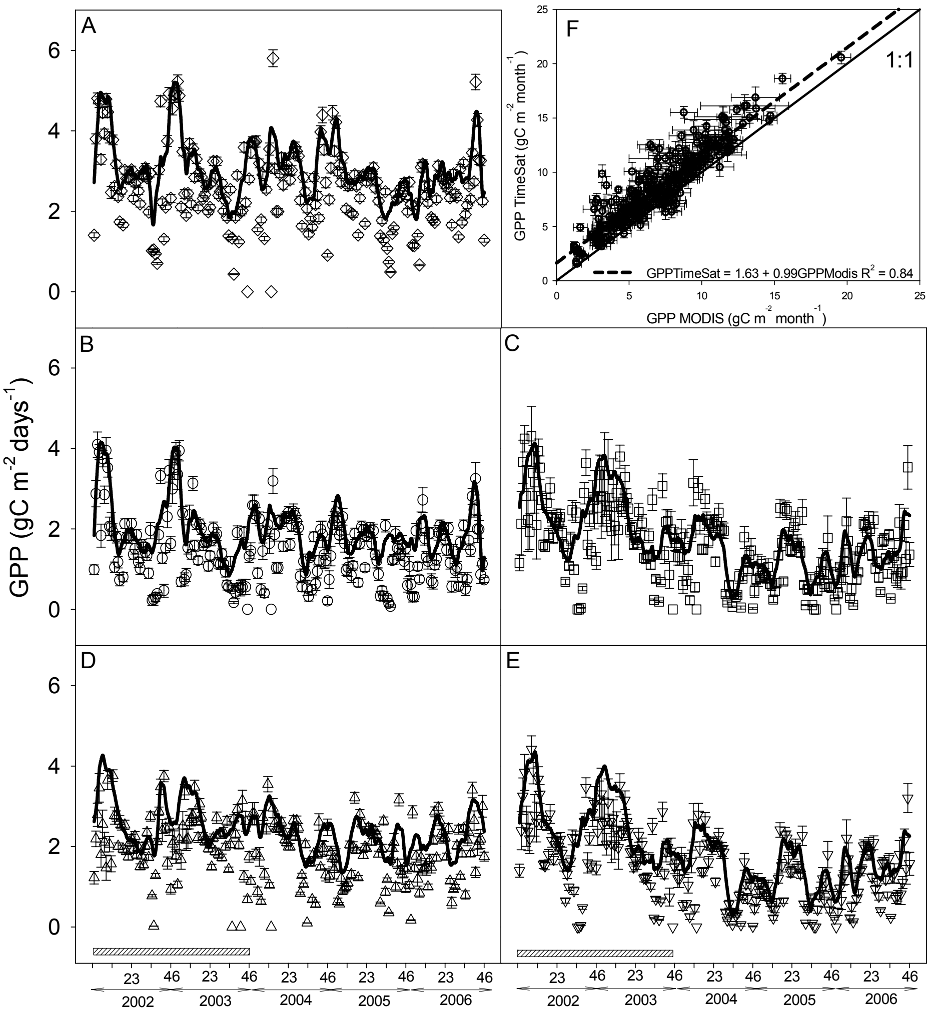

Figure 5 – Daily averages of GPP MODIS (symbols) and GPP TIMESAT 2.3 (solid lines) from 2002 to 2006 in 8 day composite, for (A) eucalypt plantations (◇) in the north of Minas Gerais, cerrado in the north (B) (O) and west (C) (□) of Minas Gerais, coffee plantation in the south (D) (△) and west (E) (▽) of Minas Gerais. Error bars represent the standard error of 5 observations. Horizontal bar on x axis indicate the ENSO event during the sample period. (F) - the regression of LSWI TimeSat in relation to LSWI Modis was calculated on a monthly basis (32 days).

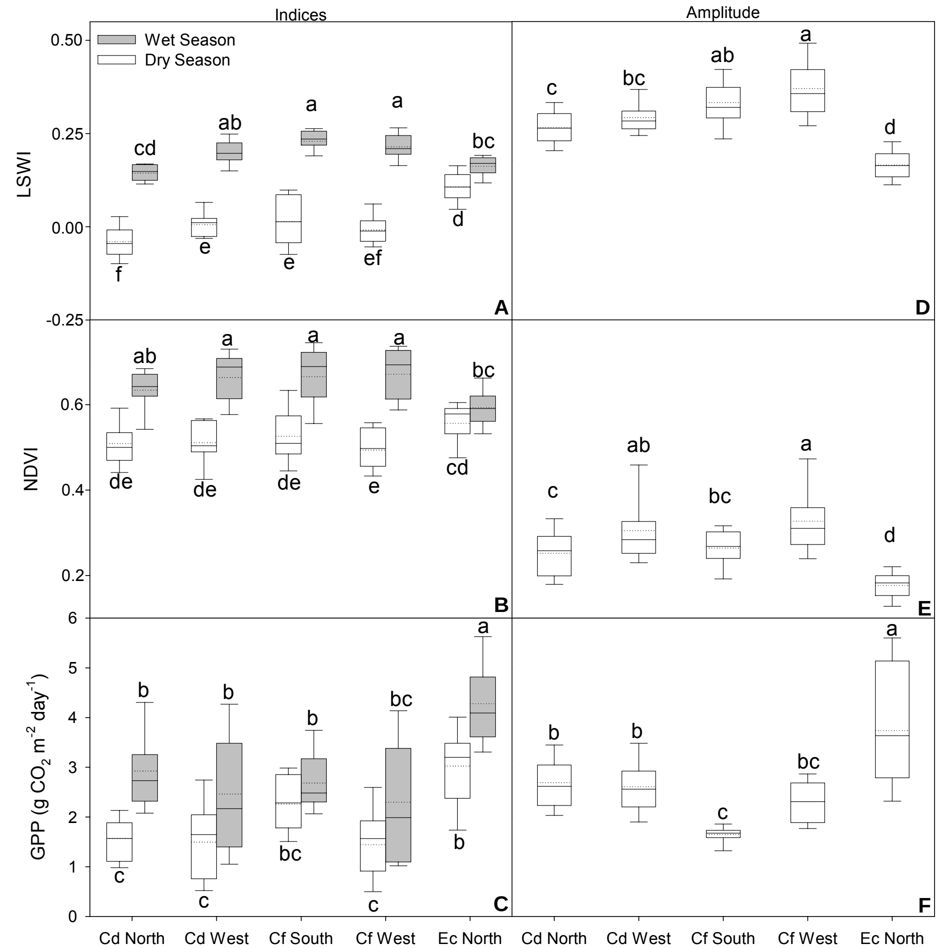

Figure 6 – Seasonal values (n=100) of (A) LSWI, (B) NDVI and (C) GPP from MODIS time-series and amplitude of seasons (n=25) of (D) LSWI, (E) NDVI and (F) GPP from TIMESAT time-series observed from 2002 to 2006, distributed in relation to ecosystems in three study sites in Minas Gerais. From left to right: cerrado north (Cd North), cerrado west (Cd West), coffee south (Cf South), coffee west (Cf West) and eucalypt (Ec North). The solid and the dotted lines in the box plots indicate the median and the average of the raw data, respectively. The top and bottom of the boxes indicate the 25th and the 75th percentiles, the whiskers above and below the boxes indicate the 90th and 10th percentiles. Categories that do not share the same letter are significantly different at $P<0.05$.

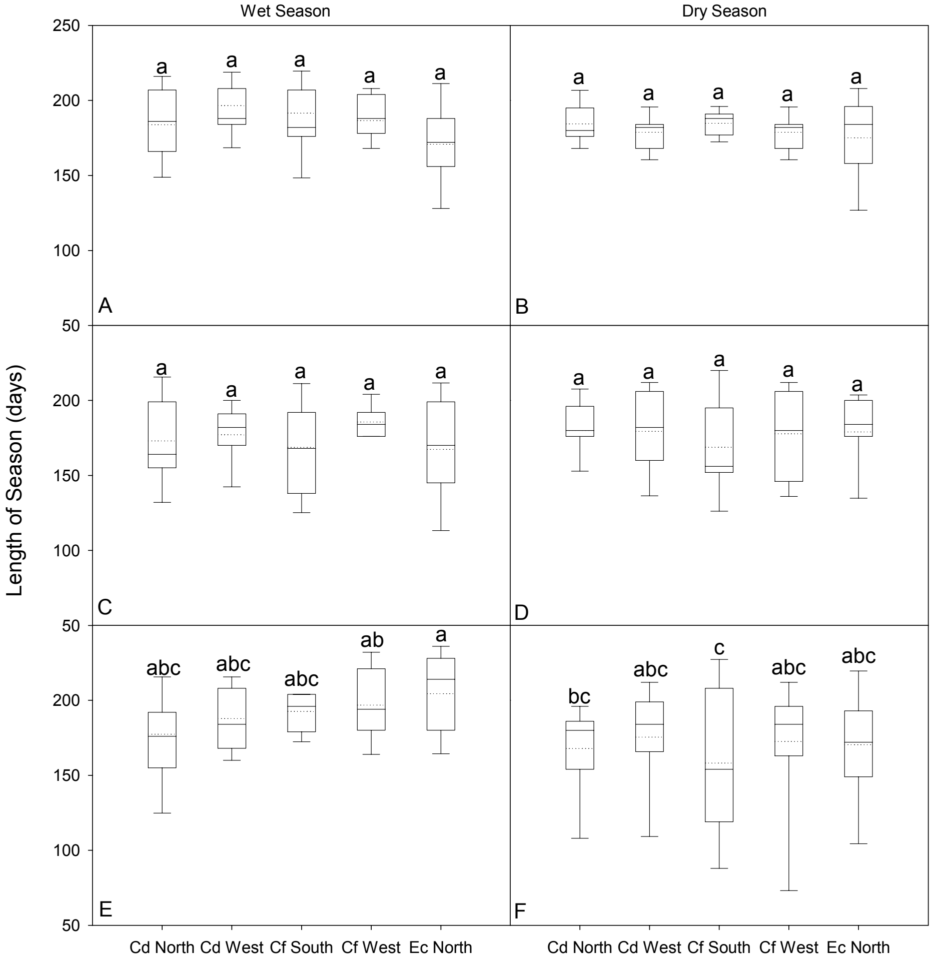

Figure 7 – Length of seasons (n=25) according to TIMESAT time-series of (A, B) LSWI, (C, D) NDVI and (E, F) GPP, distributed in relation to ecosystems in three study sites in Minas Gerais. From left to right: cerrado north (Cd North), cerrado west (Cd West), coffee south (Cf South), coffee west (Cf West) and eucalypt north (Ec North). The solid and the dotted lines in the box plots indicate the median and the average of the raw data, respectively. The top and bottom of the boxes indicate the 25th and the 75th percentiles, the whiskers above and below the boxes indicate the 90th and 10th percentiles. Categories that do not share the same letter, in the horizontal sense, are significantly different at P<0.05.

The GPP in the three sample sites indicated that the higher production occurred in the beginning of the observational period, with a generalized tendency of decreasing in the next years (Figure 5). The highest amplitude was observed for eucalypt, and the lowest for coffee in the south and west of Minas Gerais (Figure 6F). The eucalypt showed the longest wet season, and the cerrado in the north, the shortest. Coffee plantations in the south of the state showed shorter dry seasons in relation to the other ecosystems; however, the differences among ecosystems were not significant (Figure 7E).

The NDVI GIMMS, showed the seasonality and values of NDVI similar to the observed values in MODIS time-series, even with the differences in temporal and spatial resolutions (Figure 8). The long-term NDVI revealed that the effects of seasonality were more evident in coffee plantations, with higher values in the wet season, than in the ecosystems of the north of Minas Gerais (Figures 8 B, C). The values of NDVI of cerrado and eucalypt along 22 years were, in general, smaller but more constant than the ones observed for coffee, with no differences among seasonal averages. In general, the ENSO events did not influence the NDVI of the studied ecosystems, with exception to the annual values of coffee in the south of the state (Figure 8, D).

3.2 LEAF TRAITS AND ECOSYSTEM STRUCTURE

Our literature survey showed that the values of net photosynthetic rate of the functional types of cerrado wood plants ranged from 3 - 18.5 $\mu mol.m^{-2} s^{-1}$, with higher values observed for semideciduous and evergreen species (Figure 9A). The values observed for coffee were, in general, the lowest, ranging from 0.8 to 9.4 $\mu mol.m^{-2}s^{-1}$, whereas for eucalypt the values were the highest, ranging from 3.1 to 19.9 $\mu mol.m^{-2}s^{-1}$. In general, the maximum values were observed in the wet season, although the differences between seasonal averages were not significant.

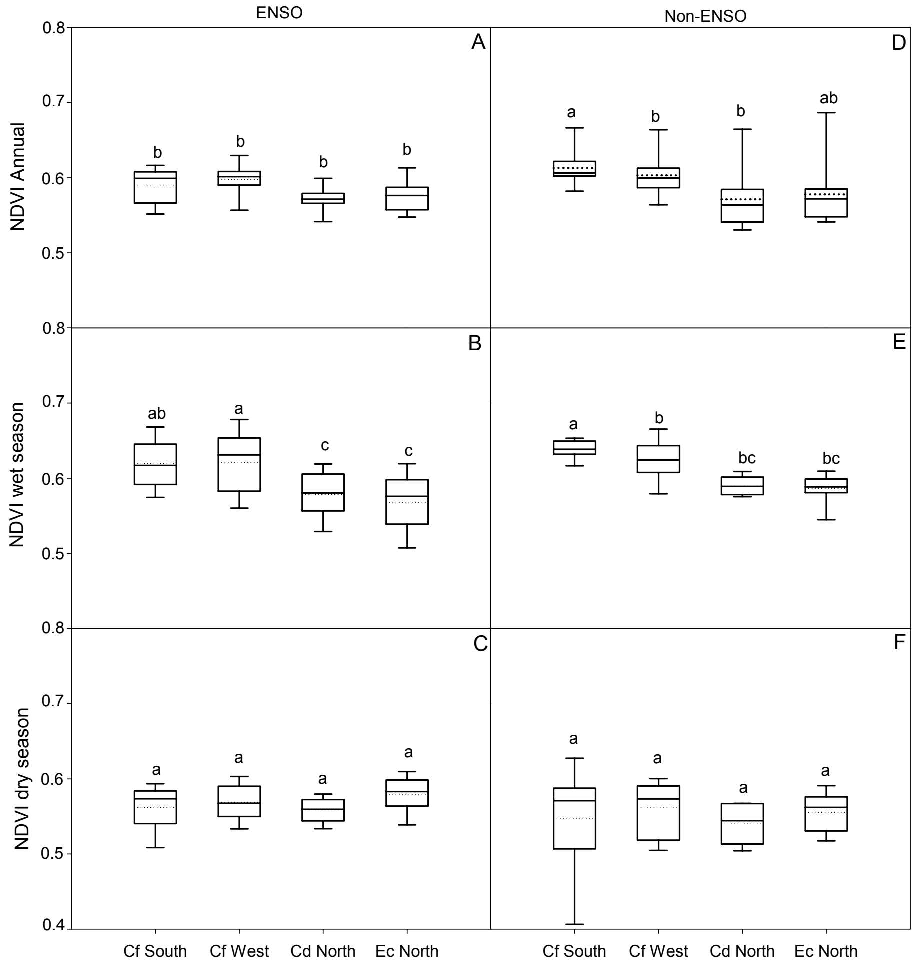

Figure 8 – Average annual and seasonal NDVI values from GIMMS time-series distributed in relation to the influence of ENSO events (n=12) (A, B, C) and without ENSO influences (non-ENSO - D, E, F) (n=10). From left to right: coffee south (Cf South), coffee west (Cf West), cerrado north (Cd North), eucalypt north (Ec North). The solid and the dotted lines in the box plots indicate the median and the average of the raw data, respectively. The top and bottom of the boxes indicate the 25th and the 75th percentiles, the whiskers above and below the boxes indicate the 90th and 10th percentiles. Categories that do not share the same letter, in the horizontal sense, are significantly different at P<0.05.

The values of stomatal conductance (gs) were higher in the wet season for all functional types of cerrado species. Coffee and eucalypt showed similar values of gs between seasons (Figure 9B). Although the values of gs observed for coffee in the dry season were smaller than the values observed for the other studied species, the values observed in the wet season were similar to the values of gs of the cerrado species and eucalypt observed in the dry season. Among the functional types of cerrado, the highest gs was observed for semideciduous, followed by deciduous and evergreen and finally by brevideciduous plants.

The highest averages of specific leaf area (SLA) in both seasons were observed for coffee (Figure 9C). The lowest values in the dry season were observed for semideciduous and evergreen species, which also showed higher average values of SLA in the wet season. The other studied species showed similar values between seasons. In most of the studied species, the highest values of carboxilation efficiency (Ci Ca^{-1}) was observed during the wet season (Figure 9D). However, for coffee the values observed in the dry season were higher than in the wet season, and for eucalypt they were similar between seasons.

In general, average transpiration rates were similar among seasons, whereas the maximum values were observed in the wet season, except for decidous species of cerrado, which showed maximum rates in the dry season (Figure 9E). The lowest transpiration average was observed for coffee and the highest for semideciduous. The values of water use efficiency observed for brevideciduous and deciduous species were higher in the dry than in the wet season (Figure 9F). For the other species the average values were similar, whereas the maximum values were observed in the dry season. Coffee presented the highest averages and deciduous the lowest, in the dry season.

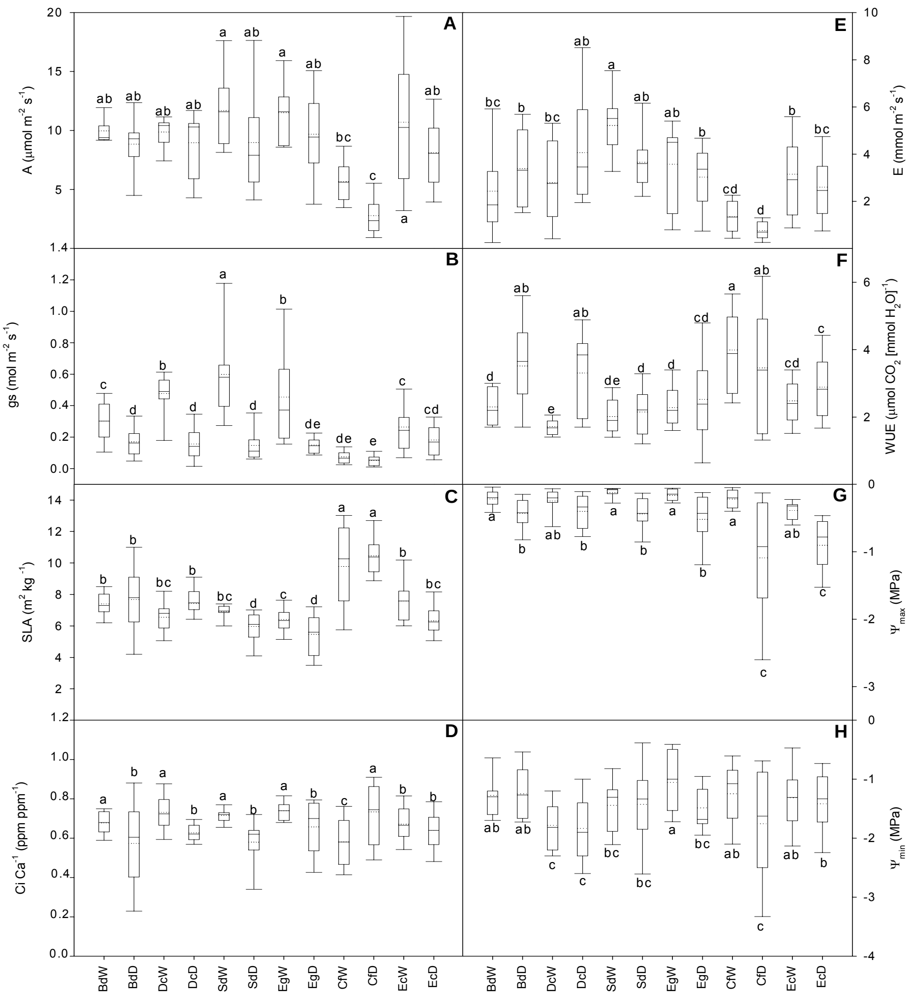

Figure 9 – Box plots of the leaf traits, grouped by species (from left to right brevidecidous, Bd; deciduous, Dc; semidecidous, Sd; evergreen, Eg; coffee, Cf and eucalypt, Ec) and by seasons (W – Wet and D – Dry). (A) net photosynthetic rate, (B) stomatal conductance, (C) specific leaf area, (D) sub-stomatal to atmosphere carbon rate, (E) transpiration rate, (F) water use efficiency, maximum(G) and minimum (H) leaf water potential. The central box in each box plot shows the interquartile range, the median (solid line) and the average (dotted line) of the raw data; whiskers indicate the 10th and 90th percentiles. Categories that do not share the same letter in the horizontal sense are significantly different at P<0.05.

The seasonal averages of maximum leaf water potential for deciduous species of cerrado were similar (Figure 9G). In the wet season all the studied species showed similar values of maximum leaf water potential. In the dry season we observed lower averages for coffee and cerrado than for cerrado functional types. Differences between seasons for the average values of minimum leaf water potential were observed for evergreen cerrado species and coffee (Figure 9H). The lowest values of minimum and maximum leaf water potential were observed for coffee, in the dry season, and for deciduous species.

In our literature survey, we could observe that the cerrado ecosystem in Minas Gerais could be represented as a 3 strata ecosystem: an intermediate stratus (4-7m), with an average density of 264 stems ha^{-1}, a low stratus (<4m), with an average density of 530 stems ha^{-1} and a high stratus (>7m), with an average density of 226 stems ha^{-1}. The highest canopy was observed for eucalypt plantations, whereas coffee plantations showed the lowest (Table 3). Coffee plantations showed the highest plant density, reaching the maximum of more than 6000 stems ha^{-1}. Cerrado showed an herbaceous layer, composed by diverse species of perennial and annual grasses. Coffee showed a very dynamic herbaceous layer due to the weed management, whereas in aged eucalypt plantations (more than 4 years old), the herbaceous stratus is more static in time. The forests of eucalypt in Minas Gerais can present a sub-canopy layer, composed especially by leguminous wood species, at an average of 800 stems ha^{-1}. The highest LAI values were observed in coffee plantations, and the lowest in cerrado (Table 3). The large deviations observed for the coffee and cerrado LAI values is caused by the seasonality. In general, the LAI of cerrado decrease by almost 50% in the dry season due to the fall of leaves in the deciduous species. The decrease of the coffee LAI in the dry season is, in general, less drastic. The fall of leaves in this ecosystem is a result of water deficits, lower temperatures and harvesting operations.

Table 3 – Average values of rooting depth (RD), canopy height (CH), density (D) and leaf area index (LAI) observed for cerrado, coffee and eucalypt. Values are average ± standard deviation of different literature sources.

Ecosystem	RD (m)	CH (m)	D (stems ha^{-1})	LAI (m^2 m^{-2})
Cerrado	7.0±1.0	9.0±5.2	1020±136	0.7±0.4
Coffee	1.5±0.3	1.6±0.2	3300±400	4.8±1.2
Eucalypt	4.5±0.7	17.5±5.0	1700±350	2.6±0.3

The underground structure of the ecosystems indicated that cerrado showed the deepest rooting, and coffee, the shallowest. Eucalypt showed intermediate rooting depth. The values of the ratio between canopy height and rooting depth for coffee was near 1.0. For eucalypt, this value was around 4 and for cerrado it ranged from 0.4 to 1.1. The variation observed for cerrado is because even shrubs present a deep tap root. The lateral rooting length is also variable among the different ecosystems. For coffee, the lateral expansion of roots was observed to be of 1.8 m from the main stem, in a layer of 0.8 m from the top soil. For eucalypt, the lateral expansion varied from 12 to 20 m in a soil layer of 1.2 m. For some cerrado species, the lateral roots can reach 7 to 10 m in a layer of almost 1.5 m.

The values of biomass allocation of cerrado systems are greater in belowground than aboveground parts. As expected for xeromorphic vegetation, the allocation of carbon for root systems growth and resistance structures is favored in relation to investments in leaves or branches. For eucalypt and coffee, 25% - 30% of the dry matter is allocated in roots. The consumption of biomass by fire in cerrado is in the order of 50% of aboveground biomass. Nevertheless, the underground biomass is not consumed by fire and it seems to be constant along time.

3.3 RELATIONSHIPS AMONG LEAF TRAITS AND ECOSYSTEMS FUNCTIONING

The analysis of the data from literature reveled that most of the variation in leaf gas exchange was related to the stomatal aperture. Within this perspective, we examined the relation of stomatal conductance to the vapour pressure deficit VPD (kPa) and to the water potential. The three ecosystems showed similar patterns of the curves of the stomatal conductance response to water availability in the atmosphere and in the soil (Figure 10). However, the slope of the curves was different among the three studied ecosystems. In our analysis, the most frequent gs value for cerrado species was 0.1 mol m^{-2} s^{-1}, which corresponded to VPD values of 2.5 kPa (Figure 10A). For coffee, such decreasing of gs with the increment of VPD was less evident, and the most frequent value of 0.06 mol m^{-2} s^{-1} could be verified at VPD values of 1.8kPa. In contrast, eucalypt maintained high values of gs (0.23 mol m^{-2} s^{-1}) even under high VPD values (2.8 kPa). We observed that eucalypt and cerrado tended to maintain higher gs values under high soil tensions, whereas gs values observed for coffee were close to zero when the values of water potential decrease from -0.5 MPa (Figure 10B).

The values of GPP correlated linearly with the net assimilation and to stomatal conductance in the three ecosystems (Figure 11). However, the determination coefficients indicated that the association of this remotely sensed index with these leaf traits was week for the three studied ecosystems. For cerrado, we observed a pattern of decrease in GPP with the increament of gs (Figure 11A). The association of net photosynthetic rate with NDVI yields high determination coefficients, especially for coffe and eucalypt (Figure 12). The determination coefficients observed for cerrado was smaller. In general, in the three ecosystems, the highest values of NDVI indicate higher net assimilation rates at the leaf level.

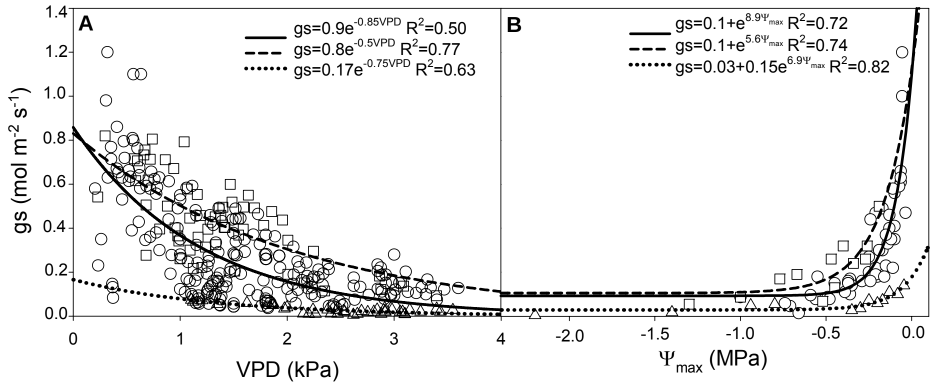

Figure 10 –The relationship of stomatal conductance (gs) to the water availability in (A) the atmosphere (vapor pressure deficit) and (B) in the soil (maximum leaf water potential) for coffee (△), eucalypt (□) and cerrado (O) in Minas Gerais, southeast Brazil.

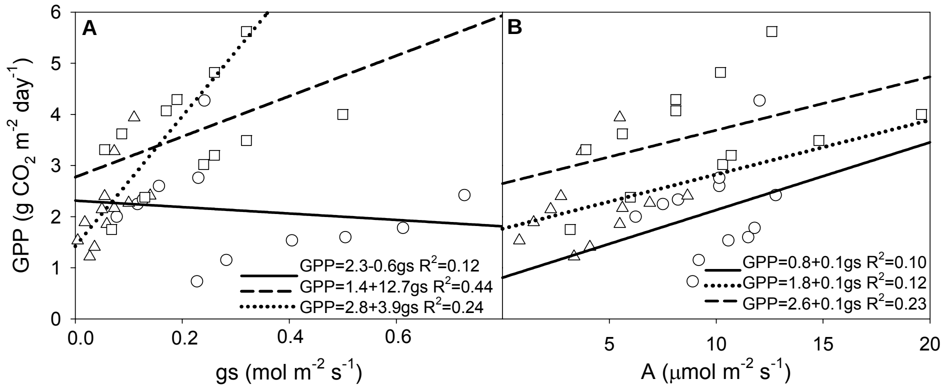

Figure 11 – The relationship of the gross primary production (GPP) with (A) stomatal conductance (gs) and (B) net assimilation (A) for coffee (△), eucalypt (□) and cerrado (O) in Minas Gerais, southeast Brazil.

Coffee and cerrado wood species showed similar responses and maximum values of net photosynthesis and leaf transpiration. These variables tended to reach the maximal values with gs values around 0.2 mol m^{-2} s^{-1} (Figures 13A, B); however, eucalypt showed incring values in the leaf gas exchange in these gs values. The water use efficiency, in the three ecosystems, tended to increase when the values of gs decrease from the 0.2 mol m^{-2} s^{-1} (Figure 13C). In general, the LSWI showed good determination coefficients with WUE, gs and Ψ_{max} (Figure 14). The values of WUE tended to increase and gs and Ψ_{max} tended to decrease drastically, in the three ecosystems, when the values of LSWI decrease from 0.15.

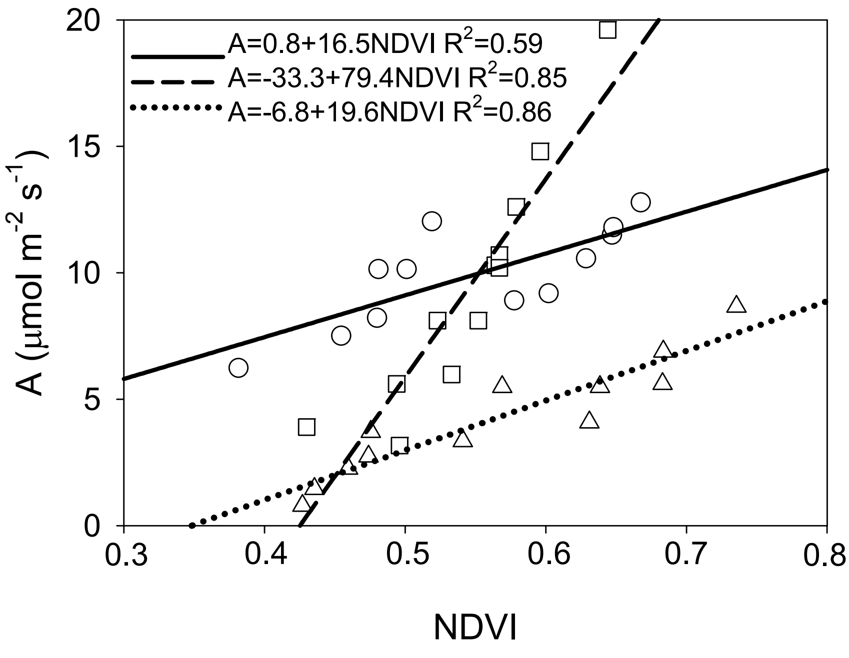

Figure 12 – The relationship of the normalized difference of vegetation index (NDVI) with the leaf net carbon assimilation (A) for coffee (△), eucalypt (☐) and cerrado (O) in Minas Gerais, southeast Brazil.

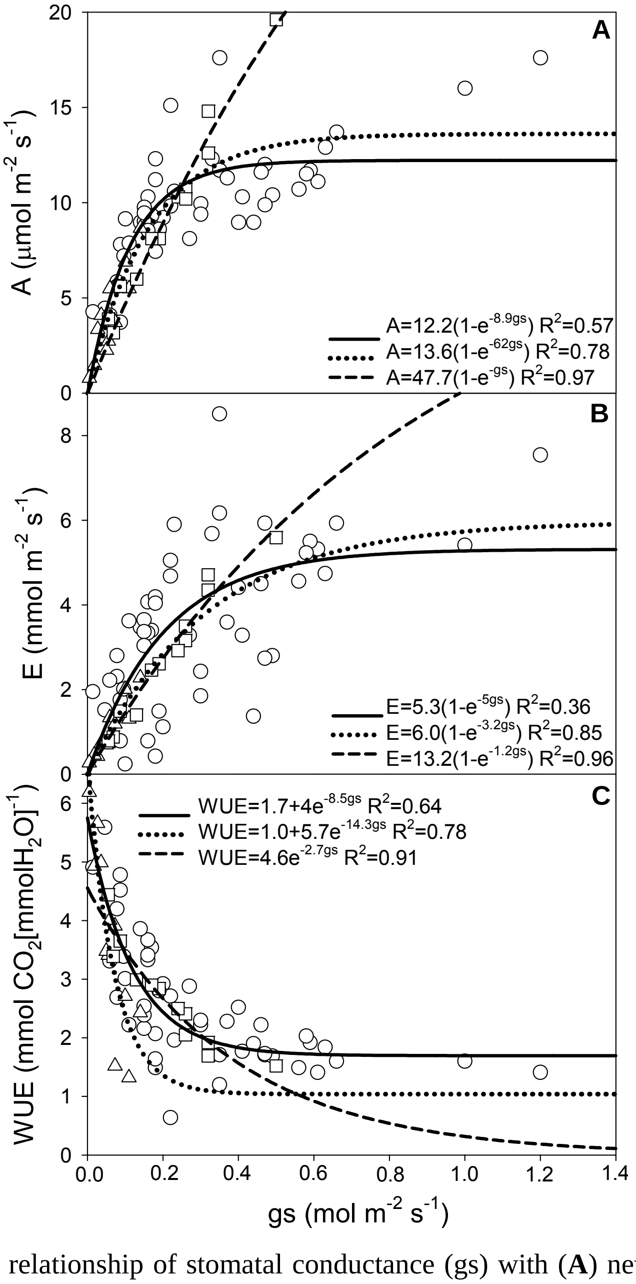

Figure 13 – The relationship of stomatal conductance (gs) with (**A**) net carbon assimilation (A), (**B**) leaf transpiration (E) and (**C**) the water use efficiency (WUE), for coffee (△), eucalypt (□) and cerrado (O) in Minas Gerais, southeast Brazil.

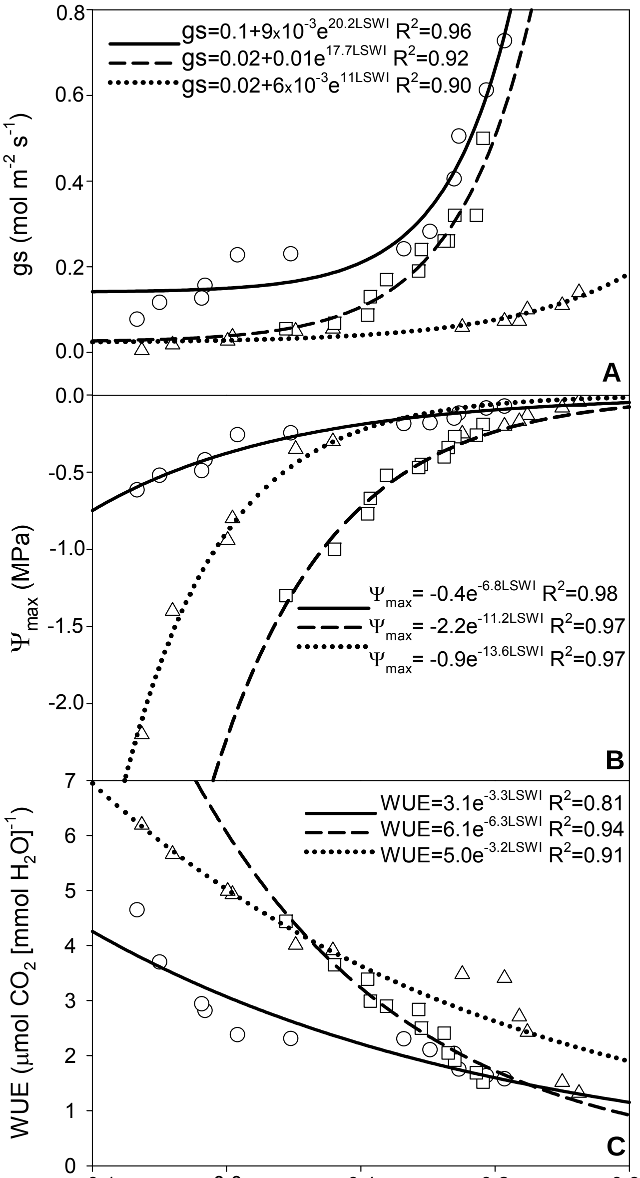

Figure 14 – The relationship of landscape surface water index (LSWI) with (**A**) the stomatal conductance (gs); (**B**) maximum leaf water potential (Ψ_{max}) and (**C**) water use efficiency (WUE) for coffee (△), eucalypt (☐) and cerrado (O) in Minas Gerais, southeast Brazil.

4 DISCUSSION

4.1 FUNCTIONING FROM REMOTELY SENSED INDICES

In our diagnostic study to assess some characteristics of the functioning of the ecosystems in the three study sites in Minas Gerais, we could observe that the seasonality is a major factor causing the variability in the responses of vegetation to environment. Similar observations were also made in other studies with the same focus (Ichii et al., 2007; Chambers et al., 2007). The seasonality in time-series of remotely sensed indices is commonly observed because the vegetation follows cycles of intense and low physiological activity in response to environmental conditions. However, the length and amplitude of seasonal cycles are ecosystem dependent being defined as function of the environmental factors limiting the physiological activity of each ecosystem (Ichii et al., 2007). The amplitude and the length of the seasonal cycles can relate the adjustment capacity of each ecosystem to environmental conditions. Therefore, the analysis of satellite based indices of vegetation is a good tool to verify the interactions among weather variability and ecosystems functioning (Grace et al., 2007).

As shown by the lower amplitude of the three indices, eucalypt and cerrado were less influenced by the seasonal water availability than coffee. Coffee plantations, however, showed a great depletion in the functional properties during the dry season, independent of the region, which has, in general, increased the amplitudes observed in this ecosystem. Some differences in the average values of vegetation indices, as well as seasonality parameters, indicated that the region was important to the variability of physiological indices observed in the ecosystems in the landscape of Minas Gerais. This major space (regions) and time (seasonality) factors seems to explain most of the observed variability of the LSWI and GPP. Furthermore, the good correlation observed among MODIS and TIMESAT for GPP and LSWI could indicate that there was no high influence of values not related to vegetation seasonality. This can be due the homogeneity of the plots used in our analysis. The selection of pixels surrounded by the same land cover class reduced errors that could be caused by intermixing of diverse land cover in a same pixel (Jönsson & Eklundh, 2002; Jönsson & Eklundh, 2004; Chambers et al., 2007).

Nonetheless, some sudden spikes were observed in the MODIS time-series, which coud be related to short-term drought stresses, which probably affected the optical properties of coffee and cerrado canopy more intensively. The results observed for NDVI GIMMS, in relation to seasonality and ENSO events can confirm the higher sensitivity of coffee to seasonality. This may be due to the shallowest rooting system. For the cerrado, the effects on NDVI are probably related to the deciduousness of the wood species and die-off of the herbaceous layer in the dry season, resulting in depletion in the values of this index. Another point to be considered in cerrado is the presence of frequent fires during the dry season (Castro & Kauffman, 1998).

Confirming these observations, Grace et al. (2007) discuss that droughts and fires are responsible for changes in normal patterns of NDVI. As for the spectral reflectance-based vegetation indices, it has been widely reported that, as a consequence of decrease in the greenness of leaves, vegetation under water deficit shows a decrease in reflectance in the near-infrared bands, an increased red reflectance in the chlorophyll active band, and a consequent blue shift on the red edge (Peñuelas et al., 1997; Sims & Gammon, 2002; Xiao et al., 2005). These non-standard conditions in the spectral signature of the canopies probably increased the variability of NDVI values observed in our study.

Undoubtedly, NDVI could be especially useful to study the effects of weather variability in the overall condition of the ecosystem, especially in relation to drought, and correlate these variations to the capacity of the canopy to photosynthesize (Niyogi & Xue, 2006; Sims et al., 2006; Grace et al., 2007). The strong correlation between NDVI and A, observed in the studied cases, indicated that this is a good parameter to measure photosynthetic activity in the ecosystems level in the landscape of Minas Gerais.

We also observed strong correlation of LSWI with gs and Ψ_{max}. This index has been broadly used as a vegetation measure related to canopy and soil moisture condition instead of chlorophyll amount being indirectly related to carbon assimilation as an indication of plant water status (Huete et al., 2005). Since seasonal drought is an important limiting factor to plant functioning in the landscape of Minas Gerais and due to the sensitivity of LSWI to detect water availability fluctuations, this would be a good index to infer about the vegetation functioning at the leaf and canopy level in the studied ecosystems of the Minas Gerais landscape.

In spite of the the good results obtained for NDVI and LSWI, we could observe a low seasonal variation in the values of GPP for coffee and cerrado, as expected by the great seasonal variations in NDVI, LSWI, in the physiological parameters at the leaf level and in the seasonal LAI values. The week correlation of GPP with these variables could be due to the algorithm used to calculate the MODIS GPP product, which considerate meteorological parameters to estimations of the light use efficiency, without any implications on the effects of water stress in decreasing carbon assimilation and photoinhibition, which is important to assimilation at the leaf level (Medrano et al., 2002; Kosugi et al., 2006). Other evidence for the week correlation of GPP with other variables could be related to the grass layer of cerrado, which can play an important role in the carbon assimilation of this ecosystem (Miranda et al., 1997; Vourlitis et al., 2001). For those reasons, studies focused on the field validation of the GPP MODIS product for the ecosystems of Minas Gerais should be performed to verify the spectral signatures related to the seasonal variations in the LAI, in carbon availability in the mesophyll and in the contribution of carbon assimilation of the grass layers to the ecosystem GPP, including spectral signatures related to the Fapar of the different ecosystems and ecosystems components in the landscape of Minas Gerais.

In summary, the results showed that the seasonality is the factor driving the variability in the functioning of ecosystems in Minas Gerais. Therefore the understanding of the effects of seasonal water-limitation on the water and carbon fluxes can give insights about the carbon sequestration and landscape vulnerability to extreme events. Therefore, these observations could be relevant to the implementation of simulation models of the landscape functioning, and should be considered in the assessment of landscape vulnerability to climate changes in Minas Gerais.

4.2 FUNCTIONING FROM LEAF TRAITS

As showed by the results from remotely sensed functioning, the major source in the variability of leaf traits, among different species, was also related to seasonality. Moreover, the variations of the gas exchange parameters (A, E, WUE and $Ci.Ca^{-1}$) could be attributed to the variations in the values of gs. Some aspects of the control of gs over leaf A and E was discussed for cerrado (Miranda et al., 1997; Eamus et al., 1999; Meinzer et al., 1999; Bucci et al., 2005), largely observed in coffee in Minas Gerais (Da Matta et al., 2003; Silva et al., 2004; Oliveira et al., 2006) and pointed out as an important factor influencing eucalypt yield in plantations of the Brazilian southeast (Lima et al., 2003; Tatagiba et al., 2007).

The results showed that, in the three ecosystems, the water availability in the soil or in atmosphere exerted, more or less, a degree of control in gs, and consequently in the gas exchanges. Cerrado and eucalypt, even with the access to water in deeper soil layers, closed the stomata in response to VPD and Ψ_{max}. Coffee was more sensitive to variations in the water availability than cerrado and eucalypt, probably due to the shallow root system. Using heat dissipation probes to measure sap flow, Meinzer et al. (1999), observed strong stomatal limitation of transpiration before midday in some cerrado species during the dry season, and associate that observation with high VPD values. Moreover, Almeida & Landsberg (2003) studied the gs control by VPD in southeast Brazilian eucalypt plantations, and Silva et al. (2004) and Oliveira et al. (2006) demonstrated the great importance of VPD in the leaf processes of *Coffea arabica* L. cropped in Minas Gerais. Further analysis of the available literature suggested that the mentioned patterns are general for C3 plants, as the case of the species under study (Medrano et al., 2002).

Because plant functioning depends strongly on the ability of stomata to control the water loss at the same time that the carbon assimilation happens, perturbations in this control at leaf level can impact the patterns of plant growth and production at the ecosystem level. Such changes should directly impact the carbon budget and the ability of ecosystems to use water efficiently (Medrano et al., 2002; Kosugi et al., 2006; Potts et al., 2006). Based on correlations of gs with A and E, it was possible to infer the main patterns of stomatal conductance defining gas exchange controls in the three ecosystems. These relations were very similar among species and allow the definition of threshold gs values from which the plants decrease the carbon assimilation and the transpiration, increasing the water use efficiency in response to drought. Similar patterns of regulation of gas exchange by gs were observed by Medrano et al. (2002), who discuss the role of gs as a reference parameter to measure the sensitivity of functioning, at the leaf level, to drought in C_3 plants. In fact, many gas exchange parameters are strongly correlated with stomatal conductance, due to the integrated down-regulation of the whole photosynthetic process by CO_2 availability in the mesophyll.

We showed some gs thresholds, based on the results of literature survey. The definition of threshold values of gs is important for the calibration of simulation models, to scale from the leaf level to the stand level and to study the temporal and spatial dynamics of ecosystem functioning related to weather variability (Lavorel et al., 1999; Hulme, 2005; Wright et al., 2005b). The connections among dominant leaf traits could be seen as the first step towards the prediction and simulation of ecosystem processes. As discussed by Días et al (1999), the relations of traits at the leaf level may represent some operational advantages since it provides an insight into ecosystem functioning. Furthermore, given a certain scenario of future climatic and land use conditions, and assuming that those links are consistent, leaf traits may be used as a proxy for vulnerability predictions and ecosystem responses in time. In this context, the analysis of leaf traits and canopy processes could be a useful empirical input to modeling water and carbon fluxes on a regional scale in Minas Gerais.

4.3 SCALING CONSIDERATIONS

We presented some regression equations among leaf traits and remotely sensed parameters aiming to give an initial step toward to the linkages of leaf to canopy functioning of ecosystems in Minas Gerais, related to seasonality. However, predicting ecosystem behavior from leaf-scale traits, as well as predicting leaf traits from remotely sensed parameters, could be more complex. The complexity arises from the multiple interactions and feedbacks among plant, atmosphere, soil and weather at different space time scales. For example, Kosugi et al. (2006) observed some of the most important parameters for the evaluation of forest carbon uptake with a multi-layer analysis in the physiological characteristics of leaf gas exchange and concluded that the assessment of seasonal variation in leaf stomatal and physiological attributes modify ecosystem-scale fluxes. However, the links between the leaf processes and the ecosystem processes were not well established in his work.

In our study, the high determination coefficients between leaf and canopy functioning indicated the trend in the variables behavior. As expect, the correlations of variables from different sources and of different scales of time and space can simple give a first insight about the influence of leaves on mass and energy fluxes of the integrated ecosystem-environmental system in Minas Gerais. As an example, considering that LSWI and NDVI are consistent indices to measure functioning at the landscape level, as well as the control of gas exchange by gs is a consistent pattern at the leaf level, the relationship between LSWI and gs and NDVI and A can be worked out to up and downscaling functioning in the ecosystems of Minas Gerais. These results confirmed that the processes at the leaf level are critical to influence ecosystem functioning, governing ecosystem carbon and water balance as also observed in other studies (Field et al., 1995; Rambal et al., 2003; Osmond et al., 2004; Kosugi et al., 2006).

It may be possible to overcome some of the challenges of scaling from leaf to canopy through increased understanding and linking of processes that adjust plant physiology in relation to ecosystems responses to seasonality. Such exercises should be able to work out data at the leaf level and ecosystem level to upscale and downscale functional and dynamical properties of the ecosystem. The remotely sensed indices at the ecosystem level should be taken into account in this process, especially for the parameterization of such approaches. The scaling exercises would generate information to support and enhance simulation models as well as the representations of the role of physiological processes in determining the responses to climate changes at the landscape level.

5 REFERENCES

ALMEIDA, A. C.; SOARES, J. V. Comparação entre uso de água em plantações de *Eucalyptus grandis* e floresta ombrófila densa (mata atlântica) na costa leste do Brasil. **Revista Árvore**, Viçosa, MG, v. 27, n. 2, p. 159-170, mar./abr. 2003.

ALMEIDA, A. C.; LANDSBERG, J. J. Evaluating methods of estimating global radiation and vapor pressure deficit using a dense network of automatic weather stations in coastal Brazil. **Agricultural and Forest Meteorology**, Amsterdam, v. 18, n. 3-4, p. 237-250, Sept. 2003.

AMARAL, J. A. T.; RENA, A. B.; AMARAL, J. F. T. Crescimento vegetativo sazonal do cafeeiro e sua relação com fotoperíodo, frutificação, resistência estomática e fotossíntese. **Pesquisa Agropecuária Brasileira**, Brasília, v. 41, n. 3, p. 377-384, mar. 2006.

BARBOSA, J. P. R. A. D. **Aspectos ecofisiológicos de cafeeiros (*Coffea arabica* L.) em produção arborizados com diferentes leguminosas no Sul de Minas Gerais**. 2005, 104 p. Dissertação (Mestrado em Fisiologia Vegetal) – Universidade Federal de Lavras, Lavras.

BARROS, R. S.; MOTA, J. W. S.; MATTA, F. M.; MAESTRI, M. Decline of vegetative growth in *Coffea arabica* L. in relation to leaf temperature, water potential and stomatal conductance. **Field Crops Research**, Amsterdam, v. 54, n. 1, p. 65-72, Aug. 1997.

BARTON, C. V. M.; MONTAGU, K. D. Effect of spacing and water availability on root: shoot ratio in *Eucalyptus camaldulensis*. **Forest Ecology and Management**, Amsterdam, v. 221, n. 1-3, p. 52–62, Jan. 2006.

BATALHA, M. A.; MANTOVANI, W. Reproductive phenological patterns of cerrado plant species at the Pé-De-Gigante reserve (Santa Rita do Passa Quatro, SP, Brazil): a comparison between the herbaceous and woody floras**. Revista brasileira de Biologia**, Rio de Janeiro, v. 60, n. 1, p.129-145, fev. 2000.

BRASIL. Ministério da Agricultura e Reforma Agrária. Secretaria Nacional de Irrigação. Departamento Nacional de Meteorologia. **Normais Climatológicas:** 1961-1990. Brasília, 1992. 84 p.

BRIGATTI, R. A.; FERREIRA, M.; SILVA, A. P.; FREITAS, M. **Estudo comparativo do comportamento de alguns híbridos de *Eucalyptus* spp**. Piracicaba: IPEF, 1980. (Circular Técnica, n. 123).

BUCCI, S. J.; GOLDSTEIN, G.; MEINZER, F. C.; FRANCO, A. C.; CAMPANELLO, P.; SCHOLZ, F. G. Mechanisms contributing to seasonal homeostasis of minimum leaf water potential and predawn disequilibrium between soil and plant water potential in neotropical savanna trees. **Trees**, Victoria, v. 19, n. 3, p. 296-304, May 2005.

BUCCI, S. J.; GOLDSTEIN, G.; MEINZER, F. C.; FRANCO, A. C.; CAMPANELLO, P.; VILLALOBOS-VEGA, R.; BUSTAMANTE, M.; MIRALLES-WILHELM, F. Nutrient availability constrains the hydraulic architecture and water relations of savannah trees. **Plant, Cell and Environment**, Oxford, v. 29, n. 12, p. 2153-2167, Dec. 2006.

BUCCI, S. J.; GOLDSTEIN, G.; MEINZER, F. C.; SCHOLZ, F. G.; FRANCO, A. C. Functional convergence in hydraulic architecture and water relations of tropical savanna trees: from leaf to whole plant. **Tree Physiology**, Victoria, v. 24, n. 8, p. 891-299, Aug. 2004a.

BUCCI, S. J.; SCHOLZ, F. G.; GOLDSTEIN, G.; MEINZER, F. C.; STERNBERG, L. S. L. Dynamic changes in hydraulic conductivity in petioles of two savanna tree species: factors and mechanisms contributing to the refilling of embolized vessels. **Plant, Cell and Environment**, Victoria, v. 26, n. 10, p. 1633-1645, Dec. 2003.

BUCCI, S. J.; SCHOLZ, F. G.; GOLDSTEIN, G.; MEINZER, F. C.; HINOJOSA, J. A.; HOFFMANN, W. A.; FRANCO, A. C.; BUSTAMANTE, M. Processes preventing nocturnal equilibration between leaf and soil water potential in tropical savanna woody species. **Tree Physiology**, Victoria, v. 24, n. 10, p. 1119-1127, Oct.2004b.

CAI, Z. Q.; CHEN, Y. J.; GUO, Y. H.; CAO, K. F. Responses of two field-grown coffee species to drought and re-hydration. **Photosynthetica**, Prague, v. 43, n. 2, p. 187-193, 2005.

CARR, M. K. V. The water relations and irrigation requirements of coffee. **Experimental Agriculture,** Cambridge, v. 37, n. 1, p. 1-6, Jan. 2001.

CARVALHO, L. M.; SILVA, E. A. M.; AZEVEDO, A. A.; MOSQUIM, P. R.; CECON, P. R. Aspectos morfofisiológicos das cultivares de cafeeiro Catuaí-Vermelho e Conilon. **Pesquisa Agropececuária Brasileira**, Brasília, v. 36, n. 5, p. 411-416, maio 2001.

CASTRO, E. A. de.; KAUFFMAN, B. Ecosystem structure in the Brazilian Cerrado: a vegetation gradient of aboveground biomass, root mass and consumption by fire. **Journal of tropical Ecology**, Cambridge, v. 14, n. 3, p. 263-268, May 1998.

CHAMBERS, J. Q.; ASNER. G. P.; MORTON. D. C.; ANDERSON, L. O.; SAATCHI, S. S.; ESPÍRITO-SANTO, F. D. B.; PALACE, M.; SOUZA JR., C. S. Regional ecosystem structure and function: ecological insights from remote sensing of tropical forests. **Trends in Ecology and Evolution**, London, v. 22, n. 8, p. 415-423, Aug. 2007.

DAMASCOS, M. A.; RONQUIM, C. C.; PRADO, C. H. B. A. Gas exchange and plant growth after defoliation on *Leandra lacunosa*, a cerrado woody species with continuous leaf production. **Brazilian Archives of Biology and technology,** Curitiba, v. 48, n. 6, p. 967-974, Nov./Dec.2005.

DaMATTA, F. M. **Desempenho fotossintético do cafeeiro em resposta a tensões abióticas.** 1995. 67 p. Tese (Doutorado) – Universidade Federal de Viçosa, Viçosa, MG.

DaMATTA, F. M. ; CHAVES, A. R. M.; PINHEIRO, H. A.; DUCATTI, C.; LOUREIRO, M. E. Drought tolerance of two field-grown clones of *Coffea canephora*. **Plant Science**, Clare, v. 164, n. 1, p. 111-117, Jan. 2003.

DaMATTA, F. M.; MAESTRI, M. Photoinhibition and recovery of photosynthesis in *Coffea arabica* and *C. canephora*. **Photossynthetica**, Prague, v. 34, n. 3, p. 439-446, 1997.

DaMATTA, F. M.; MAESTRI, M.; BARROS, R. S. Photossynthetic performance of two coffee species under drought. **Photossynthetica**, Prague, v. 34, n. 2, p. 257-264, 1997a.

DaMATTA, F. M.; MAESTRI, M.; MOSQUIN, P. R.; BARROS, R. S. Phothossintesis in Coffee (*Coffea arabica* and *C. canephora*) as affected by winter and summer conditions. **Plans Science**, Clare, v. 128, n. 1, p. 43-50. Sept. 1997b.

DIAS, P. C.; ARAUJO, W. L.; MORAES, G. A. B. K.; BARROS, R. S.; DaMATTA, F. M. Morphological and physiological responses of two coffee progenies to soil water availability. **Journal of Plant Physiology,** Jena, v. 64, n. 12, p. 1639-1647, Dec. 2007.

DÍAZ, S.; CABIDO, M.; ZAK, M.; MARTÍNEZ CARRETERO, E.; ARANÍBAR, J. Plant functional traits, ecosystem structure and land-use history along a climate gradient in central-western Argentina. **Journal of Vegetation Science**, Uppsala, v. 10, n. 5, p. 651-660, Oct. 1999.

EAMUS, D.; MYERS, B.; DUF, G.; WILLIAMS, D. Seasonal changes in photosynthesis of eight savanna tree species. **Tree Physiology**, Victoria, v. 19, n. 10, p. 665–671, oct. 1999.

FAHL, J. I.; CARELLI, M. L. C.; MENEZES, H. C.; GALLO, P. B.; TRIVELIN, P. C. O. Gas exchange, growth, yield and beverage quality of *Coffea arabica* cultivars grafted on to *C. canephora* and *C. congensis*. **Experimental Agriculture**, New York, v. 37, p. 241-252, Apr. 2001.

FAHL, J. I.; CARELLI, M. L. C.; VEGA, J.; MAGALHAES, A. C. Nitrogen and irradiance levels affecting net photosynthesis and growth of young coffee plants /*Coffea arabica*/ L. **Journal of Horticultural Science**, Kent, v. 69, n. 1, p.161-169, Jan. 1994.

FIELD, C. B.; GAMON, J. A.; PENUELAS, J. Remote sensing of terrestrial photosynthesis. In: SCHULZE, E. D.; CALDWELL, M. M. (Ed.). **Ecophysiology of Photosynthesis.** Berlin**:** Springer Verlag, 1995. p. 511-527.

FRANCO, A. C.; LUTTGE, U. Midday depression in savanna trees: coordinated adjustments in photochemical efficiency, photorespiration, CO_2 assimilation and water use efficiency. **Oecologia**, New York, v. 131, n. 3, p. 356-365, May 2002.

FRANCO, A. C.; BUSTAMANTE, M.; CALDAS. L. S.; GOLDSTEIN, G.; MEINZER, F. C.; KOZOVITS, A. R.; RUNDEL, P.; CORADIN, V. T. R. Leaf functional traits of neotropical savanna trees in relation to seasonal water deficit. **Trees**, Victoria, v. 19, n. 3, p. 326-335, May 2005.

FREITAS, R. B.; OLIVIERA, L. E. M.; FILHO, N. D.; SOARES, A. M. Influência de diferentes níveis de sombreamento no comportamento fisiológico de cultivares de café (*Coffea arabica* L.). **Ciência e Agrotecnologia**, Lavras, v. 27, n. 4, p. 804-810, jul./ago. 2003.

GÓMEZ, L. F.; LÓPEZ, J. C.; RIAÑO, N. M.; LÓPEZ, Y.; MONTOYA, E. C. Diurnal changes in leaf gas exchange and validation of a mathematical model for coffee (*Coffea arabica* L.) canopy photosynthesis. **Photosynthetica**, Prague, v. 43, n. 4, p. 575-582, 2005.

GRACE, J.; NICHOL, C.; DISNEY, M.; LEWIS, P.; QUAIFE, T.; BOWYER, P. Can we measure terrestrial photosynthesis from space directly, using spectral reflectance and fluorescence?. **Global Change Biology**, Oxford, v. 13, n. 7, p. 1484-1497, July 2007.

GRACE, J.; SAN JOSE, J.; MEIR, P., MIRANDA, H. S.; MONTES, R. A. Productivity and carbon fluxes of tropical savannas. **Journal of Biogeography**, Oxford, v. 33, n. 3, p.387–400, Mar. 2006.

HOFFMANN, W. A.; FRANCO, A. C.; MOREIRA, M. Z.; HARIDASAN, M. Specific leaf area explains differences in leaf traits between congeneric savanna and forest trees. **Functional Ecology**, Oxford, v. 19, n. 6, p. 932–940, Dec. 2005a.

HOFFMANN, W. A.; SILVA JR., E. R.; MACHADO, G. C.; BUCCI, S. J.; SCHOLZ, F. G.; GOLDSTEIN, G.; MEINZER, F. C. Seasonal leaf dynamics across a tree density gradient in Brazilian savanna. **Oecologia**, New York, v. 145, n. 2, p. 307-316, Sept. 2005b.

HULME, P. E. Adapting to climate change: is there scope for ecological management in the face of a global threat?. **Journal of Applied Ecology**, Cambridge, v. 42, n. 5, p. 784 – 794, Oct. 2005.

HURTT, G. C.; MOORCROFT, P. R.; PACALA, S. W.; LEVIN, S. A. Terrestrial models and global change: challenges for the future. **Global Change Biology**, Oxford, v. 4, p. 581 - 590; June 1998.

ICHII, K.; HASHIMOTO, H.; WHITE, M. A.; POTTER, C.; HUTYRA, L. R. HUETE, A. R.; MYNENI, R. B.; NEMANI, R. R. Constraining rooting depths in tropical rainforests using satellite data and ecosystem modeling for accurate simulation of gross primary production seasonality. **Global Change Biology**, Oxford, v. 13, n. 1, p. 67–77, Jan. 2007.

INOUE, M. T.; RIBEIRO, F. A. Fotossíntese e transpiração de clones de *Eucalyptus grandis* e *E. saligna*. **IPEF**, n. 40, p.15-20, dez. 1988.

JACKSON, P. C.; MEINZER, F. C.; BUSTAMANTE, M.; GOLDSTEIN, G.; FRANCO, A. RUNDEL, P.W. CALDAS, L. IGLER, E.; CAUSIN, F. Partitioning of soil water among tree species in a Brazilian Cerrado ecosystem. **Tree Physiology**, Victoria, v.19, n. 11, p. 717-724, Sept. 1999.

JÖNSSON, P.; EKLUNDH, L. Seasonality extraction by function fitting to time-series of satellite sensor data. **IEE Transactions on Geoscience and Remote Sensing**, New York, v. 40, n. 8, p. 1824-1832, Aug. 2002.

JÖNSSON, P.; EKLUNDH, L. TIMESAT - a program for analyzing time-series of satellite sensor data. **Computers & Geosciences**, Oxford, v. 30, n. 8, p. 833-845, Oct. 2004.

KONRAD, M. L. F.; SILVA, J. A. B.; FURLANI, P. R.; MACHADO, E. C. Trocas gasosas e fluorescência da clorofila em seis cultivares de cafeeiro sob estresse de alumínio. **Bragantia**, Campinas, v. 64, n. 3, p. 339-347, jul./set. 2005.

KOSUGI, Y.; TAKANASHI, S.; MATSUO, N.; TANAKA, K.; TANAKA, H. Impact of leaf physiology on gas exchange in a Japanese evergreen broad-leaved forest. **Agricultural and Forest Meteorology**, Amsterdam, v. 139, n. 3-4, p. 182–199, Oct. 2006.

LABOURIAU, L. G. **Problemas da fisiologia ecológica dos cerrados**. São Paulo: USP, 1963. 276 p.

LAVOREL, S.; McINTYRE, S.; GRIGULIS, K. Plant response to disturbance in a Mediterranean grassland: How many functional groups? **Journal of Vegetation Science**, Uppsala, v. 10, n. 5, p. 661-672, Oct. 1999.

LEITE, G. L. D.; VELOSO, R. V. S.; ZANUNCIO, J. C.; FERNANDES, L. A.; ALMEIDA, C. I. M. Phenology of *Caryocar brasiliense* in the Brazilian cerrado region. **Forest Ecology and Management**, Amsterdam, v. 236, n. 2-3, p. 286-294, Dec. 2006.

LELES, P. S. S.; REIS, G. G.; REIS, M. G. F.; MORAIS, E. J. Crescimento, produção e alocação de matéria seca de *Eucalyptus camaldulensis* e *E. pellita* sob diferentes espaçamentos na região de cerrado, MG. **Scientia Florestalis**, Piracicaba, n. 59, p. 77-87, jun. 2001.

LEMOS-FILHO, J. P. de. Fotoinibição em três espécies do cerrado (*Annona crassifolia*, *Eugenia dysenterica* e *Campomanesia adamantium*) na estação seca e na chuvosa. **Revista Brasileira de Botanica**, São Paulo, v. 23, n. 1, p.45-50, jun./mar. 2000.

LIMA, W. P.; JARVIS, P.; RHIZOPOULOU, S. Stomatal responses of Eucalyptus species to elevated CO_2 concentration and drought stress. **Scientia Agricola**, Piracicaba, v .60, n. 2, p. 231-238, abr./jun. 2003.

MARTINS, L. F. S.; POGGIANI, F.; OLIVEIRA, R. F.; GUEDES, M. C.; GONÇALVES, J. L. M. Características do sistema radicular das árvores de *Eucalyptus grandis* em resposta à aplicação de doses crescentes de biossólido. **Scientia Forestalis,** Piracicaba, n. 65, p. 207-218, jun. 2004.

MATEUS, J.; PITA, G.; RODRIGUES, A.; OLIVEIRA, H. Seasonal evolution of the evapotranspiration regime and carbon assimilation over a *Eucalyptus globulus* plantation. **Silva Lusitana**, Lisboa, v. 14, n. 2, p. 135 - 147, dez. 2006.

MEDRANO, H.; ESCALONA, J. M.; BOTA, J.; GULÍAS, J.; FLEXAS, J. Regulation of photosynthesis of C_3 plants in response to progressive drought: stomatal conductance as a reference parameter. **Annals of Botany**, London, v. 89, p. 895-905, June 2002. Special.

MEINZER, F. C.; GOLDSTEIN G.; FRANCO, A. C.; BUSTAMANTE, M. IGLER, E.; JACKSON, P. CALDAS, L; RUNDEL, P. W. Atmospheric and hydraulic limitations on transpirations in Brasilian cerrado wood species. **Functional Ecology**, Oxford, v. 13, n. 2, p. 273-282, Apr. 1999.

MEINZER, F. C.; GOLDSTEIN, G.; JACKSON, P.; HOLBROOK, N. M.; GUTI'ERREZ, M. V.; CAVALIER, J. Environmental and physiological regulation of transpiration in tropical forest gap species: the influence of boundary layer and hydraulic properties. **Oecologia**, New York, v. 101, n. 4, p. 514-522, Apr. 1995.

MEINZER, F. C.; GRANTZ, D. A.; GOLDSTEIN, G.; SALIENDRA, N. Z. Leaf Water Relations and maintenance of gas exchange in coffee cultivars grown in drying soil. **Plant Physiology,** Rockville, v. 94, n. 4, p. 1781-1787, Dec. 1990.

MIELKE, M. S. **Regulação fisiológica e ambiental das trocas gasosas num plantio clonal de híbridos de *Eucalyptus grandis* Hill ex-Maiden**. 1999. 92 p. Tese (Doutorado em Fisiologia Vegetal) – Universidade Federal de Viçosa, Viçosa, MG.

MIGLIETTA, F.; GIOGLI, B.; HUTJES, R. W.; REICHSTEIN, M. Net regional ecosystem CO_2 exchange from airborne and ground-based eddy covariance, land-use maps and weather observations. **Global Change Biology**, Oxford, v. 13, n. 8, p. 548–560, Aug. 2007.

MIRANDA, A. C.; MIRANDA, H. S.; LLOYD, J.; GRACE, J.;FRANCEY, R. J.; MCINTYRE, J. A.;MEIR, P.; RIGGAN, P.; LOCKWOOD, R.; BRASS, J. Fluxes of carbon, water and energy over Brazilian cerrado: an analyses using eddy covariance and stable isotopes. **Plant, Cell and Environment**, Oxford, v. 20, n. 3, p. 315-328, Mar. 1997.

MORAIS, H.; MARUR, C. J.; CARAMORI, P. H.; RIBEIRO, A. M. A.; GOMES, J. C. Características fisiológicas e de crescimento de cafeeiro sombreado com guandu e cultivado a pleno sol. **Pesquisa Agropecuária Brasileira,** Brasília, v. 38, n. 9, p. 1131-1137, set. 2003.

NASCIMENTO, E. A. N.; OLIVEIRA, L. E. M.; CASTRO, E. M.; DELÚ FILHO, N.; MESQUITA, A. C.; VIEIRA, C. V. Alterações morfofisiológicas em folhas de cafeeiro (*Coffea ar*abica L.) consorciado com seringueira (*Hevea brasiliensis* Muell. Arg.). **Ciência Rural**, Santa Maria, v. 36, n. 3, p. 852-857, maio/jun. 2006.

NAVES-BARBIERO, C. C.; FRANCO, A. C.; BUCCI, S. J.; GOLDSTEIN, G. Fluxo de seiva e condutância estomática de duas espécies lenhosas sempre-verdes no campo sujo e cerradão. **Revista Brasileira de Fisiologia Vegetal**, Londrina, v. 12, n. 2, p. 119-134, ago. 2000.

NIYOGI, D.; XUE, Y. Soil moisture regulates the biological response of elevated atmospheric CO_2 concentrations in a coupled atmosphere biosphere model. **Global and Planetary Change**, Amsterdam, v. 54, n. 1-2, p. 94–108, Nov. 2006.

OLIVEIRA, C. R. M.; BARBOSA, J. P. R. A. D.; SOARES, A. M.; OLIVEIRA, L. E. M.; MACEDO, L. R. G. Trocas gasosas de cafeeiros (*Coffea arabica* L.) e seringueiras (*Hevea brasiliensis* Muell. Arg.) em diferentes sistemas de cultivo na região de Lavras, MG. **Revista Árvore**, Viçosa, MG, v. 30, n. 2, p. 197-206, mar./abr. 2006.

OLIVEIRA, L. A. M. **Desenvolvimento vegetativo e reprodutivo do cafeeiro (*Coffea arabica L.)* irrigado em diferentes épocas do ano**. 2003. 54 p. Dissertação (Mestrado em Fisiologia Vegetal) – Universidade Federal de Lavras, Lavras.

OLIVEIRA, R. S.; BEZERRA, L.; DAVIDSON, E. A.. PINTO, F.; KLINK, C. A.; NEPSTAD, D. C.; MOREIRA, A. Deep root function in soil water dynamics in cerrado savannas of central Brazil. **Functional Ecology**, Oxford, v. 19, n. 4, p. 574-581, Aug. 2005.

OLIVEIRA, T. K.; MACEDO, R. L. G.; VENTURIN, N.; BOTELHO, S. A.; HIGASHIKAWA, E. M.; MAGALHÃES, W. M. Radiação solar no sub-bosque de sistema agrossilvipastoril com eucalipto em diferentes arranjos estruturais. **Cerne**, Lavras, v. 13, n. 1, p. 40-50, jan./mar. 2007.

OSMOND, B.; ANANYEV, G.; BERRY, J.; LANGDON, C.; KOLBER, Z.; LIN, G.; MONSON, R.; NICHOL, C.; RASCHER, U.; SCHURR, U.; SMITH, S.; YAKIR, D. Changing the way we think about global change research: scaling up in experimental ecosystem science. **Global Change Biology**, Oxford, v. 10, n. 4, p. 393–407, Apr. 2004.

PAULA, N. F. **Capacidade fotossintética, deciduidade e teor de nitrogênio e fósforo em espécies lenhosas do cerrado**. 2002. 60 p. Tese (Doutorado) – Universidade Federal de São Carlos, São Carlos.

PEREIRA, M. R. R. **Comportamento fisiológico e morfológico de clones de *Eucalyptus urograndis* submetidos a diferentes níveis de água no solo**. 2006. 52 p. Dissertação (Mestrado) - Faculdade de Ciências Agronômicas, Universidade Estadual Paulista, Botucatu.

PEÑUELAS, J.; LLUSIA, J.; PINOL, J.; FILELLA, I. Photochemical reflectance index and leaf photosynthetic radiation-use-efficiency assessment in Mediterranean trees. **International Journal of Remote Sensing**, London, v. 18, n. 13, p. 2863–2868, Sept. 1997.

POTTER, C. S.; DAVIDSON, E. A.; KLOOSTER, S. A.; NEPSTAD, D.; NEGREIROS, G. H.; BROOKS, V. Regional application of an ecosystem production model for studies of biogeochemistry in Brazilian Amazonia. **Global Change Biology**, Oxford, v. 4, n. 3, p. 315-333, Mar. 1998.

POTTS, D. L.; HUXMAN, T. E.; CABLE, J. M.; ENGLISH, N. B.; IGNACE, D. D.; EITS, J. A.; MASON, M. J.; WELTZIN, J. F.; WILLIAMS, D. G. Antecedent moisture and seasonal precipitation influence the response of canopy-scale carbon and water exchange to rainfall pulses in a semi-arid grassland. **New Phytologist**, Oxford, v. 170, n. 4, p. 849–860, 2006.

PRADO, C. H. B. A.; MORAIS, J. A. P. V. de. Photosyntetic capacity and specific leaf mass in twenty wood species of Cerrado vegetation under field conditions. **Photosynthetica**, Prague, v. 33, n. 1, p. 103-112, 1997.

PRADO, C. H. B. A.; WENHUI, Z.; ROJAS, M. H. C.; SOUZA, G. M. Seasonal leaf gas exchange and water potential in a woody cerrado species community. **Brazilian Journal of Plant Physiology**, Londrina, v. 16, n. 1, p. 7-16, Jan./Apr. 2004.

RAMBAL, S.; OURCIVAL, J. M.; JOFFRE, R.; MOUILLOT, F.; NOUVELLON, Y.; REICHSTEIN, M.; ROCHETEAU, A. Drought controls over conductance and assimilation of a Mediterranean evergreen ecosystem: scaling from leaf to canopy. **Global Change Biology**, Oxford, v. 9, n. 12, p. 1813 – 1824, Dec. 2003.

ROCHA, H. R. da; FREITAS, H. C.; ROSOLEM, R.; JUÁREZ, R. I. N.; TANNUS, R. N.; LIGO, M. A.; CABRAL, O. M. R.; DIAS, M. A. F. S. Measurements of CO_2 exchange over a woodland savanna (Cerrado Sensu stricto) in southeast Brasil. **Biota Neotropica**, São Paulo, v. 2, n. 1, 2002. Disponível em: <http://www.biotaneotropica.org.br/>.

RONQUIM, C. C.; PRADO, C. H. B. A.; PAULA, N. F. de. Growth and photosynthetic capacity in two woody species of cerrado vegetation under different radiation availability. **Brazilian Archives of Biology and Technology**, Curitiba, v. 46, n. 2, p. 243-252, Apr. June 2003.

RONQUIM, J. C.; PRADO, C. H. B. A.; NOVAES, P.; FAHL, J. I.; RONQUIM, C. C. Carbon gain in *Coffea arabica* during clear and cloudy days in the wet season. **Experimental Agriciculture,** New York, v. 42, n. 2, p. 147–164, Apr. 2006.

SALESKA, S.R.; MILLAR, S.D.; MARTOS, D.M.; GOULDEN, M.L.; WOFSY, S.C.; DA ROCHA, H.R.; DE CAMARGO, P.B.; CRILL, P.; DAULE, B.C.; DE FREITAS, H.C.; HUTYRA, L.; SÉLLER, M.; KIRCHHOFF, V.; MENTON, M.; MUNGER, J.W.; PYLE, E.H.; RICE, A.H.; SILVA, H. Carbon in Amazon forests, unexpected seasonal fluxes and disturbance-induced losses. **Science**, Washington, v. 302, n. 5650, p. 1554–1557, Nov. 2003.

SCHOLZ, F. G.; BUCCI, S. J.; GOLDSTEIN, G.; MEINZER, F. C.; FRANCO, A. C.; MIRALLES-WILHELM, F. Biophysical properties and functional significance of stem water storage tissues in neotropical savanna trees. **Plant, Cell and Environment**, Oxford, v. 30, n. 2, p. 236- 248, Feb. 2007.

SILVA, A. C. da. **Indicadores fisiológicos associados à produtividade do cafeeiro (*Coffea arabica* L.) sob influência da irrigação em Lavras - MG**. 2005. 56 p. Dissertação (Mestrado) - Universidade Federal de Lavras, Lavras.

SILVA, B. C. da; CLARKE, R. T. Análise estatística de chuvas intensas na bacia do rio São Francisco. **Revista Brasileira de Meteorologia**, Jaboticabal, v. 19, n. 3, p. 265-272, 2004.

SILVA, E. A.; DaMATTA, F. M.; DUCATTI, C.; REGAZZIC, A. J.; BARROSA, R. S. Seasonal changes in vegetative growth and photosynthesis of arabic coffee trees. **Field Crops Research**, Amsterdam, v. 89, n. 2-3, p. 349–357, Oct. 2004.

SILVA, S. L. de O. **Respostas biofísicas, bioquímicas e anatômicas em plantas de *Coffea arabica* L. em condições contrastantes de disponibilidade de radiação**. 2002. 45 p. Dissertação (Mestrado em Fisiologia Vegetal) – Universidade Federal de Lavras, Lavras.

SILVA, W. da. **Interferencia de *Brachiaria brizantha* sobre *Eucalyptus citriodora* e *E. grandis*, cultivados em solos com diferentes teores de agua**. 1997. 89 p. Tese (Doutorado em Fitotecnia) – Universidade Federal de Viçosa, Viçosa, MG.

SIMS D. A.; GAMON, J. A. Relationships between leaf pigment content and spectral reflectance across a wide range of species, leaf structures and developmental stages. **Remote Sensing of Environment**, New York, v. 81, n. 2-3, p. 337– 354, Aug. 2002.

SIMS, D. A.; LUO, H.; HASTINGS, S.; OECHEL, W. C.; RAHMAN, A. F.; GAMON, J. A. Parallel adjustments in vegetation greenness and ecosystem CO_2 exchange in response to drought in a Southern California chaparral ecosystem. **Remote Sensing of the Environment**, New York, v. 103, n. 3, p. 289–303, Aug. 2006.

STAPE, J. L. **Definição do período e localização de cobertura de *Eucalyptus grandi*s em funções da dinâmica do crescimento radicular**. Piracicaba: IPEF, 1990. (Circular Técnica, 174).

STAPE, J. L.; BINKLEY, D.; RYAN, M .G.; GOMES, A. N. Water use, water limitation, and water use efficiency in a *Eucalyptus* plantation. **Bosque**, Valdivia, v. 25, n. 2, p. 35-41, 2004a.

STAPE, J. L.; BINKLEY, D.; RYAN, M. G. *Eucalyptus* production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil. **Forest Ecology and Management**, Amsterdam, v. 193, n. 1-2, p. 17–31, May 2004b.

TATAGIBA, S. D.; PEZZOPANE, J. E. M.; REIS, E. F.; DARDENGO, M. C. J.; EFFGEN, T. A. M. Comportamento fisiologico de dois clones de *Eucalyptus* na época seca e chuvosa. **Cerne**, Lavras, v. 13, n. 2, p. 149-159, abr./jun. 2007.

TUCKER, C. J.; PINZON, J. E.; BROWN, M. E.; SLAYBACK, D.; PAK, E. W.; MAHONEY, R.; VERMOTE, E.; EL SALEOUS, N. An extended AVHRR 8-km NDVI data set compatible with MODIS and SPOT vegetation NDVI data. **International Journal of Remote Sensing,** Abingdon, v. 26, n. 20, Oct. 2004.

VOURLITIS, G. L.; PRIANTE FILHO, N.; HAYASHI, M. M. S.; NOGUEIRA, J. S.; CASEIRO, F.T.; CAMPELO JUNIOR, J. H. Seasonal variations in the net ecosystem CO_2 exchange of a mature Amazonian transitional tropical forest (cerradão). **FunctionalEcology**, Oxford, v. 15, n. 3, p. 388–395, June 2001.

WHITEHEAD, D.; BEADLE, C. L. Physiological regulation of productivity and water use in *Eucalyptus*: a review. **Forest Ecology and Management**, Amsterdam, v. 193, n. 1-2, p. 113–140, May 2004.

WHITFORD, K. R.; COLQUHOUN, I. J.; LANG, A. R. G.; HARPER, B. M. Measuring leaf area index in a sparse eucalypt forest: a comparison of estimates from direct measurement, hemispherical photography, sunlight transmittance and allometric regression. **Agricultural and Forest Meteorology**, Amsterdam, v. 74, n. 3-4, p. 237-249, May 1995.

WRIGHT, I. J.; REICH, P. B.; CORNELISSEN, J. H. C.; FALSTER, D. S.; GARNIER, E.; HIKOSAKA, K.; LAMONT, B. B.; LEE, W.; OLEKSYN, J.; OSADA, N.; POORTER, H.; VILLAR, R.; WARTON, D. I.; WESTBOY, M. Assessing the generality of global leaf trait relationships. **New Phytologist**, Cambridge, v. 166, n. 2, p. 485–496, May 2005a.

WRIGHT, I. J.; REICH, P. B.; CORNELISSEN, J. H. C.; FALSTER, D. S.; GROOM, P. K.; HIKOSAKA, K.; LEE, W.; LUSK, C. H.; NIINEMETS, U.; OLEKSYN, J.; OSADA, N.; POORTER, H.; WARTON, D. I.; WESTBOY, M. Modulation of leaf economic traits and trait relationships by climate. **Global Ecology and Biogeography**, Oxford, v. 14, n. 5, p. 411-421, Sept. 2005b.

XAVIER, A. C.; SOARES, J. V.; ALMEIDA, A. C. Variação do índice de área foliar em clones de eucalipto ao longo de seu ciclo de crescimento. **Revista Árvore**, Viçosa, MG, v. 26, n. 4, p. 421-427, jul./ago. 2002.

XIAO, X. M.; ZHANG, Q. Y.; HOLLINGER, D.; ABER, J.; MOORE III, B. Modeling gross primary production of an evergreen needleleaf forest using MODIS and climate data. **Ecological Applications**, Washington, v.15, n. 3, p. 954–969, June 2005.

CHAPTER V

A bottom-up approach for the assessment of vulnerability to climate changes based on the sensitivity of functional properties to water availability of ecosystems in Minas Gerais, Brazil

ABSTRACT

BARBOSA, João Paulo Rodrigues Alves Delfino. A bottom-up approach for the assessment of vulnerability to climate changes based on the sensitivity of functional properties to water availability of ecosystems in Minas Gerais, Brazil. In:______. **Vulnerability of the Minas Gerais landscape to global changes:** an initial step to a bottom-up approach. 2008. Chap. 5, 193 p. Thesis (Agronomy/Plant Physiology) – Federal University of Lavras, Lavras.*

Currently global changes are a threat to ecosystem functioning and their vulnerability to future scenarios can be stated in function of the sensitivity and adaptation capacity of the main physiological processes to the limiting environmental factor. This work was an initial step towards the vulnerability assessment of ecosystems on the landscape of Minas Gerais, Southeast Brazil, to the global changes, using such a concept. Basically, we built databases and examined the relationships of functional process at the leaf and ecosystem levels with the relative soil water content (RWC). Three case studies were used: the north, where cerrado and eucalypt plantations were targeted; the west, with cerrado and coffee plantations, and the south, where coffee plantations were studied. The functioning of each ecosystem was evaluated by remote sensing of vegetation indices. Three indices were extracted from MODIS imagery: NDVI, LSWI and GPP. Leaf traits (A, E, gs, WUE and Ψmax) were obtained by a literature survey. The RWC was simulated by an approach based on temperature, energy balance, precipitation and vegetation and soil characteristics. The regression analysis of vegetation indices and leaf traits with RWC yield exponential equations, with inflection points between 0.6 and 0.7. We assumed that values below 0.7 were able to affect the normal functioning of the ecosystems, being a risk threshold. This threshold was used on time-series of RWC to derive indices of stress duration and stress intensity. These indices were linearly correlated to the length of the dry season and to the amplitude of seasons, extracted from remotely sensed time-series. Stress duration higher than 180 days can seriously threaten the landscape of Minas Gerais, by decreasing the functional properties of ecosystems. The database and equations generated in this study could be used in the improvement and construction of process-based mechanistic models for landscape simulation, and on prediction of ecosystems functioning in future scenarios, enhancing the conditions to the assessment of regional vulnerabilities to the global changes.

Key-words: leaf traits, ecosystem functioning, remote sensing, drought stress.

* Guidance Committee: Prof. Dr. Angela Maria Soares (Adviser), Dr. Serge Rambal - CEFE/CNRS (Co-adviser).

RESUMO

BARBOSA, João Paulo Rodrigues Alves Delfino. Uma abordagem tipo *bottom-up* para o estudo da vulnerabilidade às mudanças climáticas, baseado na sensibilidade de propriedades funcionais à disponibilidade hídrica de ecossistemas de Minas Gerais. In:______. **Vulnerabilidade da paisagem de Minas Gerais às mudanças globais:** um passo inicial para uma abordagem tipo *bottom-up*. 2008. Cap. 5, 193 p. Tese (Agronomia / Fisiologia Vegetal) – Universidade Federal de Lavras, Lavras.[*]

As mudanças climáticas são uma ameaça para os ecossistemas e a sua vulnerabilidade a cenários futuros pode ser descrita em função da sensibilidade e da capacidade adaptativa dos principais processos fisiológicos a um fator ambiental limitante. Dentro desse contexto, foram utilizadas diferentes bases de dados para avaliar as relações entre parâmetros funcionais no nível foliar e do ecossistema com o conteúdo relativo de água no solo (RWC). Três casos foram analisados: o norte, onde cerrado e eucaliptal foram estudados; o oeste, com cafezal e cerrado; e o sul, com estudos em cafezal. O funcionamento de cada ecossistema foi avaliado por três índices de sensoriamento remoto, extraídos de imagens MODIS: NDVI, LSWI e GPP. Características foliares (A, E, gs, WUE e Ψmax) foram obtidas por revisão de literatura. O RWC foi simulado com base nos valores diários de temperatura, balanço de radiação, precipitação e características da vegetação e do solo. As regressões dos índices de vegetação e de características foliares, em função do RWC, ajustaram-se em equações exponenciais, com pontos de inflexão entre 0,6 e 0,7. Assumindo-se que valores abaixo de 0,7 caracterizariam uma condição de estresse, foi estabelecido que tal valor de seria o limite de risco para o funcionamento dos ecossistemas, sendo possível derivar índices relacionados à duração e à intensidade do estresse. Tais índices foram linearmente relacionados com a duração da estação seca e com a amplitude, extraídos das séries temporais dos parâmetros de sensoriamento remoto. Valores de duração do estresse maiores que 180 dias podem afetar a paisagem de Minas Gerais pela redução do funcionamento dos ecossistemas. A base de dados e as equações geradas com esse estudo podem ser utilizadas na melhoria e construção de modelos mecanicísticos, baseados em processos, para a simulação da paisagem de Minas Gerais, bem como podem ser úteis na predição do funcionamento dos ecossistemas em cenários futuros, melhorando as condições de conhecimento da vulnerabilidade regional às mudanças globais.

Palavras-chave: características foliares, funcionamento de ecossistemas, sensoriamento remoto, estresse hídrico.

---

[*] Comitê Orientador: Prof[a]. Dr[a]. Angela Maria Soares (Orientadora), Dr. Serge Rambal - DREAM/CEFE/CNRS (Co-orientador).

1 INTRODUCTION

In recent years, studies of vegetation functioning based on simulation models provided consistent evidence that the climatic trends for the next decades will affect ecosystem functioning. Some simulations also predict potential negative impacts of warming on biodiversity, food production, carbon sequestration, water storage and other ecosystem services (Shaver et al., 2000; Chaves et al., 2002; Rambal et al., 2003; Nemani et al., 2003; Santos & Costa, 2004; Chartzoulakis & Psarras, 2005; Hulme, 2005; Niyogi & Xue, 2006; Harpole et al., 2007 among others). However, the present challenge is not only to know that climate changes are able to affect vegetation, but rather to consider the physiological and biophysical thresholds of the vulnerability of ecosystems to those changes. This knowledge would be helpful to the establishment of mitigation strategies to withstand extreme events, forecasted with higher frequency and magnitude in the ongoing climate scenarios (Watson et al., 2000; Tjoelker & Zhou, 2007).

The occurrence of extreme events seems to affect the cultivated and natural ecosystems more than the rising atmospheric CO_2 concentrations. This is because the alterations in the timing and amount of precipitation and evapotranspiration, together with warming, can impact all chemical and biological processes, limiting the carbon assimilation at all organizational levels. Moreover, it has been suggested that soil moisture mediates other factors affecting the ecosystem dynamics such as fires, heat waves, light and nutrient availability and it is the primary factor defining the responses of vegetation to environment. Therefore, the greatest obstacles to understanding the vulnerability of ecosystems to global changes lie in the functional responses, at diverse levels, resulting from interactions of processes affected by the environment (Kicklighter et al., 1999; Shaver et al., 2000; Tjoelker & Zhou, 2007; Li et al., 2007).

These interactions are dependent on the sensitivity and adaptation capacity to abiotic stressors. Thus, the responses to climate variability can be expected to vary among ecosystems in both, magnitude and intensity, depending on the properties of the dominant species, interactions among species, and the biological, physical and chemical environment (Rosenzweig et al., 2004; Lin, 2007; Hulme, 2005; Niyogi & Xue, 2006; Suttle et al., 2007; Harpole et al., 2007). In particular, the interrelations of ecosystem functioning and leaf gas exchange with environment, in water-limited areas, have been examined in function of sensitivity to soil water availability. These interrelations can give some insights about ecosystems vulnerability to weather variability, since soil moisture availability is a function of timing and amount of precipitation, temperature, wind speed, energy availability and vegetation properties (Schulze et al., 1994; Reich et al., 1999; Niinemets, 2001).

Further, analyzing leaf trait data with information on a larger scale, such as water balance, is the type of information that will greatly enhance the representations and simulations of different vegetation responses, including dynamic biological parameters of plant adjustments to environmental properties (Wright et al., 2005a; Wright et al., 2005b). Information such as this can be used to parameterize simulation models, and, consequently, have important implications for predicting the impacts of future climate change over ecosystem functioning.

The present study was undertaken to link data at local-scale environmental conditions with ecosystem and micro-scale leaf functioning, and consequently it provides an initial step toward the possibility to work with dynamic-functional models as well as to assess the vulnerability to climate changes of ecosystems in Minas Gerais in a bottom-up approach. Our objectives were: (1) examine how the effects of drought regulated the functioning of coffee, eucalypt and cerrado systems in three regions of Minas Gerais; (2)

identify equations constrained by plant characteristics and soil water status that may be used further to scale up ecosystem regulation from basic leaf-level relationships; (3) to propose directions for simulation modeling and to build a database able to support further simulation exercises in ecosystems of Minas Gerais; and finally, (4) provide insights about landscape vulnerability to climate changes in Minas Gerais using a bottom-up approach based on functioning.

2 STUDY CONDITIONS

2.1 SITES CHARACTERISTICS

This study was performed in three sites in the landscape of Minas Gerais, southeast Brazil: We study a site in the north region (15^{o}20’ to 17^{o}10’S, 42^{o}20’ to 45^{o}05’W and average 466 m of altitude) with cerrado and *Eucaliptus* sp. plantations; a site in the south (21^{o}30’ to 22^{o}00’S, 45^{o}20’ to 46^{o}05’W and 1215 m of altitude), with *Coffea arabica* L. plantations, and a last site was selected in the west of Minas Gerais (18^{o}30’ to 19^{o}00’S, 46^{o}10’ to 46^{o}50’W, and 873 m of altitude) with coffee plantations and cerrado. The three study sites laid over dystrophic, poor and deep soils with medium (approximately equal parts of sand, silt and clay) to clayey (between 35 and 60% clay and equal parts of silt and sand) texture. The declivity of the northern site ranged between 0% and 45%, between 13% to over 70% in the south and from 0% to 45% in the west of Minas. The predominant climatic type in Minas Gerais, according to Köppen’s classification is the Cwa: moist with mild dry winter (dry season – May to August) and warm summer, which concentrate more than 80% of the annual rainfall (wet season – December to March).

2.2 WEATHER AND SOIL WATER AVAILABILITY

The weather conditions from 2000 to 2006 in each study site were verified from daily values of mean air temperature and precipitation. The weather datasets were obtained from automatic weather stations of the **C**entro de **P**revisão de **T**empo e **E**studos **C**limáticos - **I**nstituto **N**acional de **P**esquisas **E**spaciais (CPTEC-INPE – accessible at http://satelite.cptec.inpe.br/PCD/pcd). We used data available in the south (3 stations – Lavras, Machado and Itajubá), north (2 stations - Januária and Salinas) and west (2 stations – Araxá and Patrocínio) to calculate anomalies in relation to published normal values (1961–1990) for each region: north (Montes Claros and Araçuaí); south (Machado and Lavras); west (Araxá and Uberaba) (Brasil, 1992).

The analysis of the anomalies observed in the dry and wet seasons (performed by box-plots, and the comparison of averages by the Tukey test at $P<0.05$), indicated that, in general, the west region of Minas Gerais showed the lowest anomalies of temperature in the wet season (Figure 1A). In the north and south of the state, the anomalies of temperature were higher in the wet season. The anomalies observed in the dry season in the north and south, in the wet season, and in the west in the dry season, were similar. The precipitation anomalies, observed in the dry season, were higher than the anomalies observed in the wet season in the three regions, nonetheless, the values stayed near the normality (Figure 1B). In the wet season, the monthly precipitation was, in general, below the normal values.

These results indicated that the analyzed period was, in general, drier and warmer than normal, with warmer dry seasons, and drier wet seasons. In the 3 regions, the precipitation of the wet season has an important role in the soil water balance, refilling the water depleted during 3 months of intense drought (June, July and August). For this reason, the average reduction of 50mm month^{-1} in the precipitation of the wet season could be important for the reduction of the annual soil water budget. This effect could be enhanced by the observed increment in the air temperature in the dry season, leading to longer and more intense dry seasons throughout years.

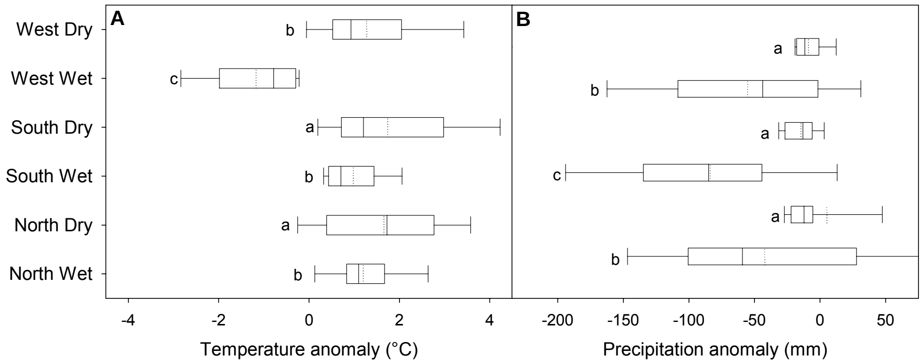

Figure1 – Monthly distribution of mean air temperature (A) and precipitation (B) anomalies in the wet (December, January, February and March) and dry (June, July, August and September) seasons from 2000 to 2006 (n=24) in the three study sites in Minas Gerais (South, West and North). The solid and the dotted lines in the box plots indicate the median and the average of the raw data, respectively. The right and left of the boxes indicate the 25th and the 75th percentiles, the left and right whiskers indicate the 90th and 10th percentiles. Categories that do not share the same letters in the vertical sense are significantly different at P<0.05.

The soil moisture, from 2000 to 2006, was assessed by a soil water balance model (Rambal, 1993) that simulated, on a daily basis, the water balance components (transpiration, evaporation and deep drainage or water yield) and the water status of the rooted soil layer based in soil, root depth and weather characteristics (mean temperature, net radiation and precipitation). In this model, the daily value of soil moisture was equal to the difference between the water storage in the rooted soil profile and the evapotranspiration. Further, this relation was expressed using the concept of **R**elative soil **W**ater **C**ontent (RWC), which is the ratio of current moisture to moisture at field capacity. The field capacity in the study sites was considered as 0.28 kg kg^{-1} (Ruiz et al., 2003) and the depth of the rooted soil as showed in figure 3.

The monthly distribution of the RWC values showed the seasonal pattern of the soil water availability in the studied ecosystems. In general, the values of RWC decreased from May to September and kept near to the field capacity (RWC = 1) from December to February (Figures 2 A, B, C). Analyzing the seasonal raw data of monthly RWC by box-plots, and comparing seasonal averages by the Tukey test at $P<0.05$, we observed in the wet season the highest RWC for cerrado in the west of Minas Gerais and the lowest for eucalypt plantations (Figure 2D). Coffee plantations, in the west and south, and cerrado in the north and west, showed intermediary RWC values in that season. In the dry season, the coffee plantations in the south of the state showed the lowest values, and cerrado in the north showed the highest RWC values.

The lower RWC values observed in the wet season for the ecosystems in the north of Minas Gerais could be explained by the lower daily rainfall rates observed in this region in relation to the south and west. However, during the dry season, the leaf-fall in cerrado and the deep rooting characteristics of cerrado and eucalypt, together with the more frequent precipitation in April and May in the north of Minas Gerais, could maintain higher values of RWC for those ecosystems in the dry season. The depletion of soil water in the coffee plantations to the south of Minas Gerais could result from higher temperatures during the winter together with the shallow rooting characteristic of the plants.

3 VEGETATION FUNCTIONING

3.1 LEAF TRAITS

As substantial works have already been published on the ecophysiology of coffee, eucalypt and functional groups of cerrado (deciduous, semideciduous, brevideciduous and evergreen), we used a literature survey as the source of information to build a database to evaluate the effects of drought on leaf functioning. We searched for data of the stomatal conductance (gs), CO_2 assimilation (A) and leaf transpiration (E). Plant water status was estimated with predawn leaf water potential values (Ψ_{max}). Most of the data have been obtained from research on mature plants, growing under normal conditions in the field or in greenhouse, with evaluations in the wet and dry seasons (chapter IV, Table2). The instantaneous leaf water use efficiency (WUE) was derived from the rate between A and E.

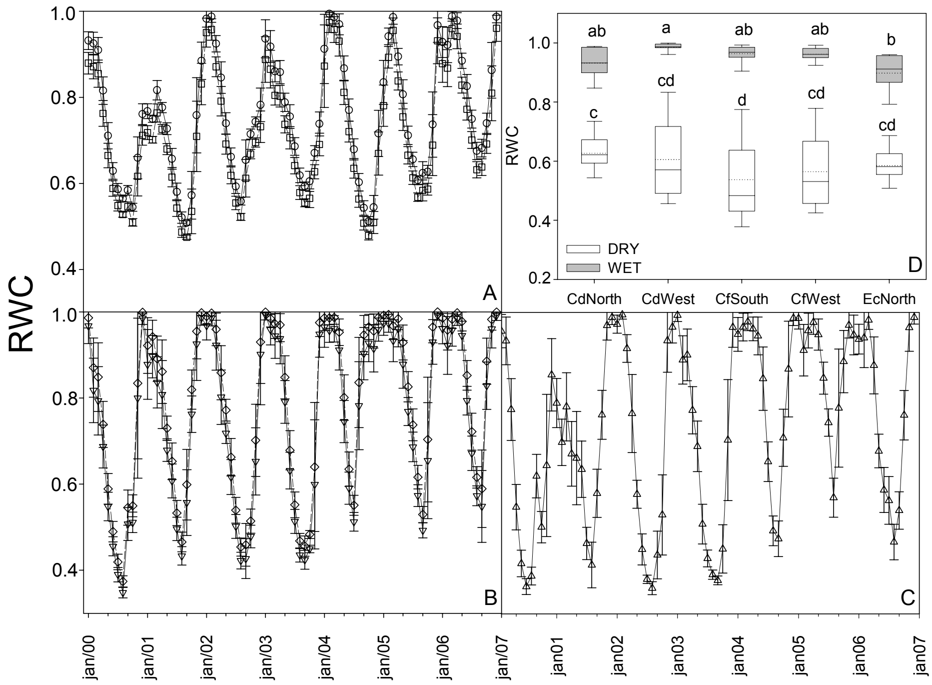

Figure 2 – Monthly Relative Water Content (RWC) simulated from 2000 to 2006 in (A) north of Minas Gerais for cerrado (○ Cd North) and eucalypt (□ Ec North), (B) south of Minas Gerais for coffee (△ Cf South) and (C) west of Minas Gerais for coffee (▽ Cf West) and cerrado (◇ Cd West). Values of RWC are averages ± standard error of days. (D) The box plots shows the monthly distribution of seasonal RWC values (n=28), the solid and the dotted lines indicate, respectively, the median and the average of the raw data. The top and bottom of the boxes indicate the 25th and the 75th percentiles, the whiskers above and below the boxes indicate the 90th and 10th percentiles. Categories that do not share the same letter are significantly different at P<0.05.

The values of A of cerrado wood species ranged from 3 to 18.5 µmol $m^{-2}s^{-1}$. For coffee, the values ranged from 0.8 to 9.4 µmol $m^{-2}s^{-1}$, and, for eucalypt, from 3.1 to 20.1 µmol $m^{-2}s^{-1}$. The values of gs observed for coffee ranged from 0.01 to 0.14 mol $m^{-2}s^{-1}$. For eucalypt, from 0.06 to 0.46 mol $m^{-2}s^{-1}$, and for cerrado from 0.01 to 1.2 mol $m^{-2}s^{-1}$. In general, transpiration rates of cerrado wood species ranged from 0.2 to 8.5 mmol $m^{-2}s^{-1}$, from 0.8 to 5.6 mmol $m^{-2}s^{-1}$ to eucalypt, and from 0.2 to 2.3 mmol $m^{-2}s^{-1}$ to coffee. For Ψ_{max}, the values ranged from -1.3 MPa for cerrado and eucalypt and from -2.3 MPa for coffee, to values near 0 MPa. The higher values of WUE were observed in the dry season, ranging from 0.9 to 5.6; 1.3 to 7.1 and 1.5 to 4.5 µmol CO_2 [mmol $H_2O]^{-1}$ for cerrado, coffee and eucalypt, respectively. The average values $\pm$ standard error of the leaf traits are presented in figure 3.

The average density of eucalypt showed intermediate values (1700 stems ha^{-1}) (Figure 3A) in relation to cerrado (1020 stems ha^{-1}) (Figure 3C) and coffee plantations, which showed the highest plant density (3300 stems ha^{-1}) (Figure 3B). However, it is noticeable that the densities of coffee and eucalypt plantations can vary according to plant spacing and techniques. The highest values of the leaf area index (LAI) were observed in coffee plantations, and the smallest in cerrado. The large deviations observed for the LAI values of coffee and cerrado is due to a seasonal effect on leaf abscission. The root system of cerrado is the deepest, and coffee has the shallowest. The values of the ratio between canopy height and rooting depth for coffee was near 1.0. For eucalypt, this value was around 4 and for cerrado 0.8. The lateral rooting length is also variable among the different ecosystems. For coffee, the lateral expansion of roots was observed to be of 1.8 m from the main stem, in a layer of 0.8 m from the top soil. For eucalypt, the lateral expansion varied from 12 to 20 m in a soil layer of 1.2 m. For some cerrado species, the lateral roots can reach 7 to 10 m in a layer of 1.5 m.

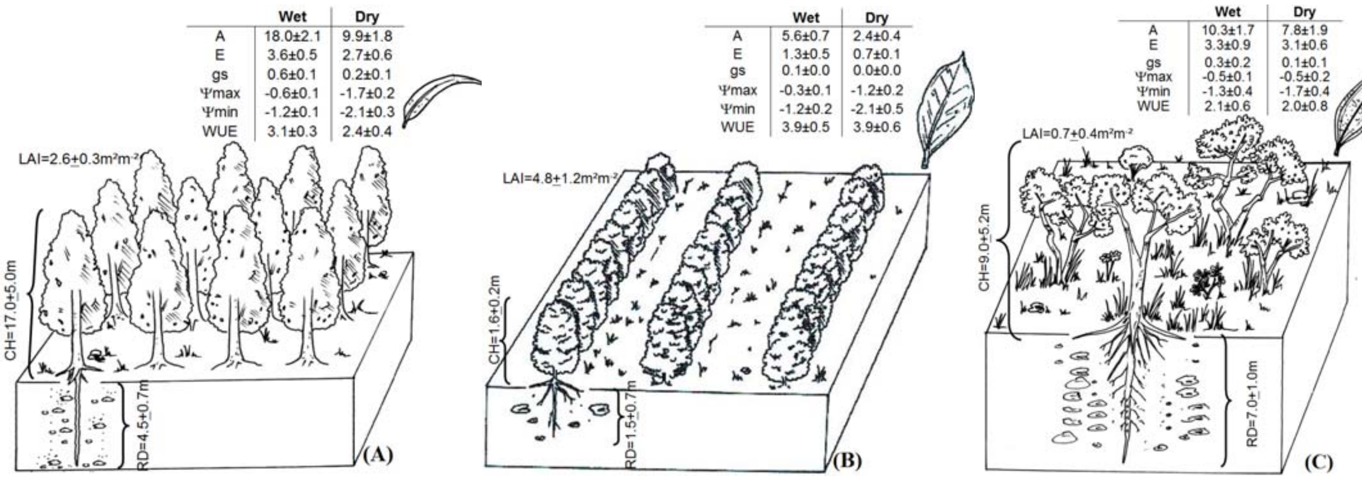

Figure 3 – A representation of the three studied ecosystems in the landscape of Minas Gerais: (A) eucalypt plantation, (B) coffee plantation and (C) cerrado. The average ± standard error of leaf traits observed in the wet and in the dry seasons and structural properties are shown: Ψmin – minimum leaf water potential, MPa; Ψmax – maximum leaf water potential, MPa; WUE – leaf water use efficiency, μmol CO_2 [mmol H_2O]$^{-1}$; E – leaf transpiration rate, mmol m^{-2} s^{-1}; A - net CO_2 assimilation, μmol m^{-2} s^{-1}; gs – stomatal conductance, mol m^{-2} s^{-1}; LAI – leaf area index, m^2m^{-2}; RD – root system depth, m; CH – canopy height, m.

3.2 REMOTE SENSING OF ECOSYSTEM FUNCTIONING

The seasonal characteristics of ecosystem functioning were obtained by remote sensing of vegetation indices. The indices NDVI (**N**ormalized **D**ifference of **V**egetation **I**ndex), LSWI (**L**and **S**urface **W**ater **I**ndex) and GPP (**G**ross **P**rimary **P**roduction) were assessed from 2002 to 2006 by MODIS (**Mod**erate Resolution **I**maging **S**pectroradiometer) products, in 8 days composite at spatial resolution of 500m (NDVI and LSWI) and of 1km (GPP). The MODIS imagery was treated to remove occasional sudden spikes caused by atmospheric effects or non vegetated areas, by the TIMESAT 2.3 software (Jönsson & Eklundh, 2004). The data generated by this fitting process was used for the extraction of the length and amplitude of seasons (Jönsson & Eklundh, 2002).

The plots used in this study were selected over thematic maps of the study sites. The land cover maps were generated from Landsat TM images from 2002 (west, spatial resolution of 30m), from 2005 (south, spatial resolution of 10m) and from 2003 (north, spatial resolution of 30m). The maps from west and southern sites were obtained from the Laboratório de Geoprocessamento-Empresa de Pesquisa Agropecuária de Minas Gerais (GEOSOLOS-EPAMIG), and the northern vegetation map from the Laboratório de Estudos em Manejo Florestal-Universidade Federal de Lavras (LEMAF-UFLA). We selected 5 plots of each studied ecosystems, each plot was one replicate of the variance analysis (ANOVA) and comparison of averages by the test of Tukey at $\alpha = 5\%$.

In general, the lowest values of NDVI, LSWI and GPP were observed in the dry season. The values of NDVI and LSWI in the wet season were higher in the ecosystems in the west and south (Figures 4A, B). In the dry season, eucalypt plantations showed the highest values of LSWI, whereas cerrado, in the north, the lowest. For GPP, eucalypt showed the highest values in the wet season (Figure 4C). In the dry season the values were similar with the values observed for coffee in the south of the state.

In general, there were no differences in amplitudes of LSWI between the cerrado ecosystems and coffee plantations, at different sites (Figure 4D). However, the amplitudes for coffee were higher than those of cerrado. The amplitudes of LSWI and NDVI observed for eucalypt were the lowest (Figures 4D, E). The NDVI amplitudes in the west were similar for coffee and cerrado. The coffee in the south showed amplitude similar to the cerrado in the north of Minas Gerais, whereas those values were smaller than the ones observed for coffee in the west. The NDVI amplitudes observed for eucalypt were the smallest. The highest amplitude was observed for eucalypt, and the lowest for coffee in the south and west of Minas Gerais (Figure 4F). The length of the dry season observed for LSWI, NDVI and for GPP in the different study sites showed similar values along the analysis period (Figures 4 G, H, I).

4 SENSITIVITY ANALYSES

The sensitivity of leaf traits and ecosystem functioning to the soil water status was examined by regression analysis, to identify equations that constrained plant functioning by soil water availability. We correlated the values of the 10th, 25th, 75th, 90th percentiles, the average and the median of the normal distribution of the seasonal raw data of A, E, WUE, gs, Ψ_{max}, NDVI, GPP and LSWI with RWC. The regression models were adjusted by the least square method and the equation parameters were analyzed using the *t-test* at $P<0.01$. In general, the regressions of the physiological properties in function of RWC were fitted by an exponential model, that showed the decrease of functioning with the decrease of the RWC, reaching the maximum values at RWC = 1.0 (Figures 5 and 6). The inflection point of the adjusted equations in function of RWC ranged from 0.6 and 0.7. At values below this threshold, we could observe a generalized depletion in the functional properties of the three studied ecosystems.

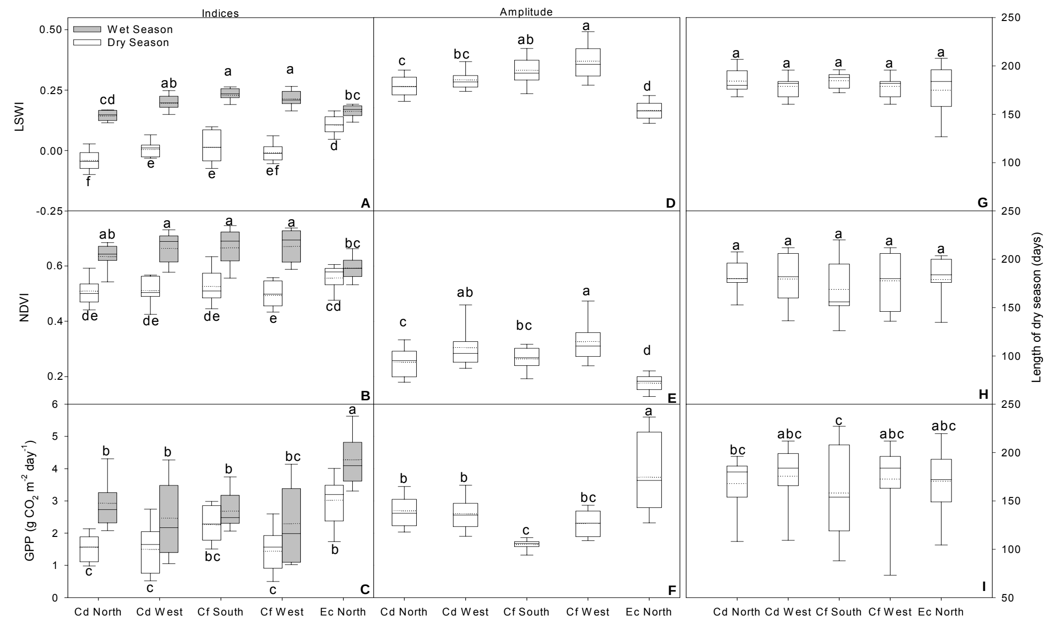

Figure 4 – Seasonal distribution of monthly values (n=100) of (A) LSWI, (B) NDVI and (C) GPP, amplitude of seasons (n=25) of (D) LSWI, (E) NDVI and (F) GPP and length of the dry season (n=25) of (G) LSWI, (H) NDVI and (I) GPP observed from 2002 to 2006, in relation to ecosystems in three study sites in Minas Gerais. From left to right: cerrado north (Cd North), cerrado west (Cd West), coffee south (Cf South), coffee west (Cf West) and eucalypt (Ec North). The solid and the dotted lines in the box plots indicate, respectively, the median and the average of the raw data. The top and bottom of the boxes indicate the 25th and the 75th percentiles, the whiskers above and below the boxes indicate the 90th and 10th percentiles. Categories that do not share the same letter, in the horizontal sense, are significantly different at $P<0.05$.

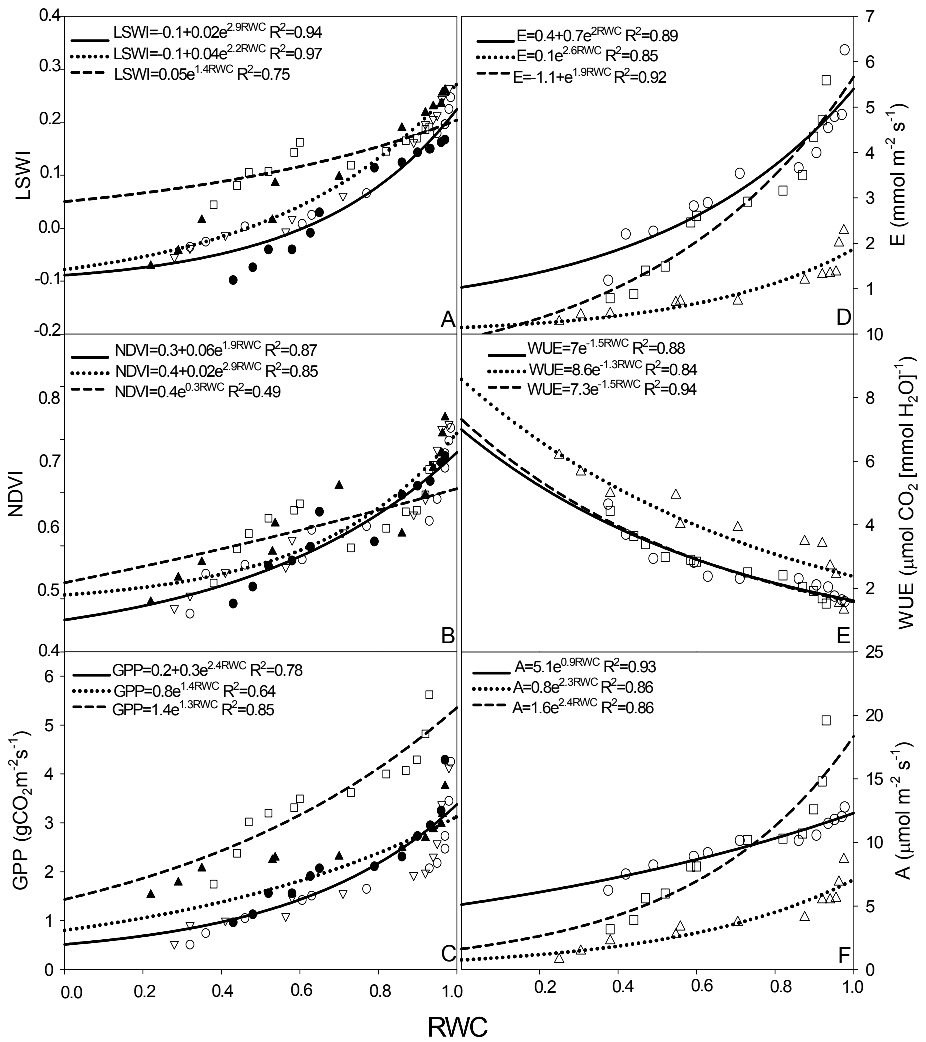

Figure 5 – Relationships between RWC and: land surface water index (LSWI) (**A**), normalized vegetation difference index (NDVI) (**B**) and of gross primary production (GPP) (**C**) observed for cerrado in the north (●) and in the west (○), for coffee in the south (▲) and west (▽)and eucalypt in the north of Minas Gerais (□). And relationships between of RWC and: transpiration rate (E) (**D**), water use efficiency (WUE) (**E**) and net carbon assimilation (A) (**F**) observed for cerrado (○), coffee (△) and eucalypt (□) in Minas Gerais. The solid, dotted and dashed lines are the fitted exponential equations for cerrado, eucalypt and coffee, respectively.

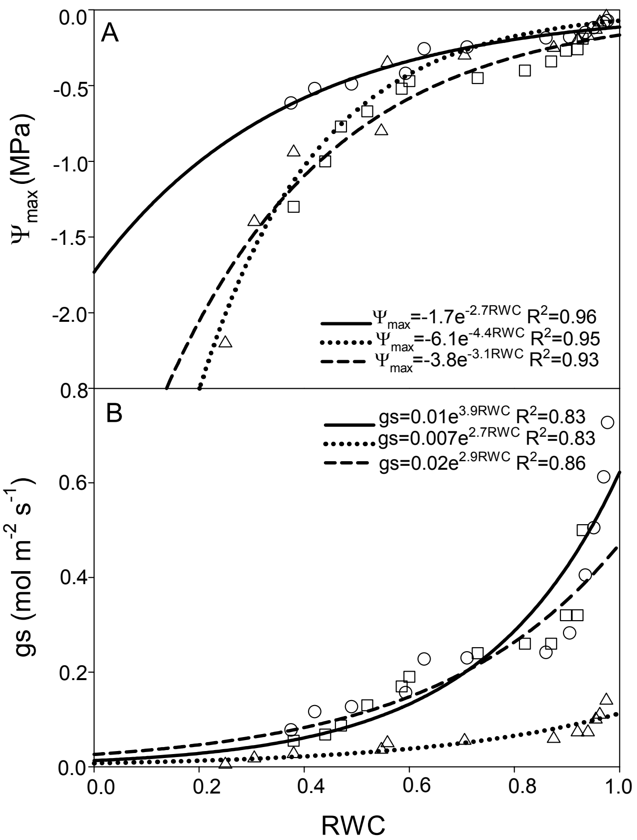

Figure 6 - The relationship between soil relative water content (RWC) and: stomatal conductance (gs) (**A**) and maximal leaf water potential (Ψ_{max}) (**B**) observed for cerrado (○), coffee (△) and eucalypt (□) in Minas Gerais.

However, for the same RWC values, eucalypt was less sensitive than coffee and cerrado at the ecosystem level, showing higher NDVI, LSWI and GPP values (Figures 5A, B, C). Cerrado and the coffee plantations showed similar equations to describe the remote sensed indices in function of RWC, indicating a similar sensitivity to soil water availability depletion. Nonetheless, the equations describing the leaf traits sensitivity of eucalypt plantations and cerrado to soil moisture were more similar (Figures 5D, E, F). Although the leaf trait values were lower for coffee, the response of this species, at the leaf level, to the depletion in the soil moisture was less drastic, except for the plant water status, measured by the Ψ_{max} (Figures 6B).

5 VULNERABILITY ASSESSMENT

Assuming that soil moisture mediates the influence of other factors affecting the ecosystems (as fires, light, heat waves, nutrient availability and high CO_2 concentrations) (Rosenzweig et al., 2004; Lin, 2007; Hulme, 2005; Harpole et al., 2007; Suttle et al., 2007) and considering the plant physiology as the primary process defining ecosystems functioning and landscape dynamics, we used the results of the sensitivity analysis to assess the vulnerability of the landscape of Minas Gerais to climate changes. The concept used for the evaluation of vulnerability was adapted from Luers et al. (2003) and from Metzger et al. (2006). It basically consisted of first: to define the limit of risk through a RWC threshold from where the ecosystems have their functioning threatened. And second, from that point we measured susceptibility in terms of the magnitude, duration and frequency of this stress situation.

We defined the threshold value of RWC = 0.7 based on the generalized value of the inflection point of the regression curves of the sensitivity analysis. Values of RWC below this threshold were considered as a stress condition, able to affect the normal functioning of at least one feature of one ecosystem in the landscape. The amount of time that RWC values were lower than 0.7 was the stress duration and the integral of values below this threshold in time was the stress intensity (Figure 7).

The stress duration and intensity observed for the studied ecosystems from 2000 to 2006, in three regions of Minas Gerais are showed in table 1. In general, the intensity and duration values tended to decrease from 2000 to 2006. In fact, the values of temperature and precipitation anomalies, observed along the study period, decrease from 2000 to 2006. The stress indices observed for coffee were the highest, whereas cerrado showed the lowest values. Moreover, considering all values observed, the stress intensity increased exponentially with the increment of stress duration (Figure 8). Considering the inflection point of the curve (around 180 days), it was possible to observe a drastic increase in the stress intensity when stress duration increased from this value.

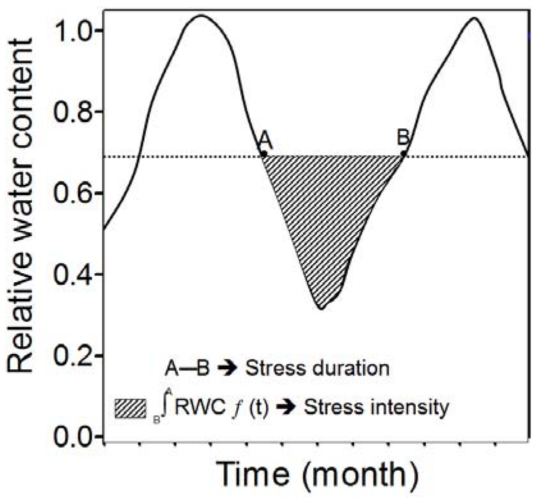

Figure 7 – The definition of intensity and duration of stress based on the threshold value of RWC=0.7 and on the time-series of RWC.

We correlated the amplitude of seasons and the length of the dry season, extracted from the TimeSat 2.3 time-series of remotely sensed indices, with the stress intensity and duration (Figure 9). High determination coefficients were obtained for the linear regressions of length of dry seasons of LSWI, GPP and NDVI in function of the stress duration for all studied ecosystems (Figures 9D, E, F). As mentioned before, the values of the ecosystem function indices were, in general, lower in the dry season for all the ecosystems (Figure 4), indicating decrease of functional processes in this season, related to depletion of the water storage in the soil. Long droughts can be thus associated to long stress periods and loss of functional activity of vegetation. Considering that LSWI, a measure of surface moisture content at the canopy level, was well correlated to the RWC and the length of the dry season of this index was also well correlated with the stress duration (Figure 9D), there is the possibility of remotely sensed assessment of the stress indices derivate from these sensitivity analysis.

Table 1 – Intensity and Duration of stress observed for cerrado, eucalypt and coffee in three regions of Minas Gerais, southeast Brazil, from 2000 to 2006.

Ecosystem	Cerrado		Coffee		Eucalypt
Region	North	West	South	West	North
Year	Stress Duration (days)				
2000	201	206	208	224	224
2001	170	125	190	158	240
2002	131	161	193	188	213
2003	151	166	194	178	199
2004	160	67	103	76	184
2005	153	82	47	102	174
2006	66	74	147	83	106
	Stress Intensity				
2000	20.7	24.2	40.0	50.4	36.8
2001	20.9	8.8	23.9	25.2	40.0
2002	10.4	15.5	40.2	37.6	34.6
2003	13.6	15.0	38.7	41.3	31.7
2004	20.0	1.0	11.4	13.2	28.7
2005	9.1	2.3	3.0	17.2	26.7
2006	1.3	1.0	16.7	13.4	13.0

For the amplitudes of the time-series of remotely sensed indices, we also verified a linear increment in function of stress intensity (Figures 9A, B, C). However, only eucalypt showed high determination coefficients. The weak relationship observed for the other studied ecosystems could be associated to the fact that amplitudes indicate the difference in the functional properties between the wet and dry seasons, whereas the stress intensity associate only to decrease in the functionality during the dry season. The tendency of amplitude increase with the stress intensity increment confirm that the depletion of the soil water has an important effect in the ecosystem functioning. Moreover, it opens the possibility of inferring that the ecosystems are somewhat adapted to withstand the standard duration and intensity imposed by the dry season every year. However, the effects of extreme drought events can increase the stress effects over functioning linearly.

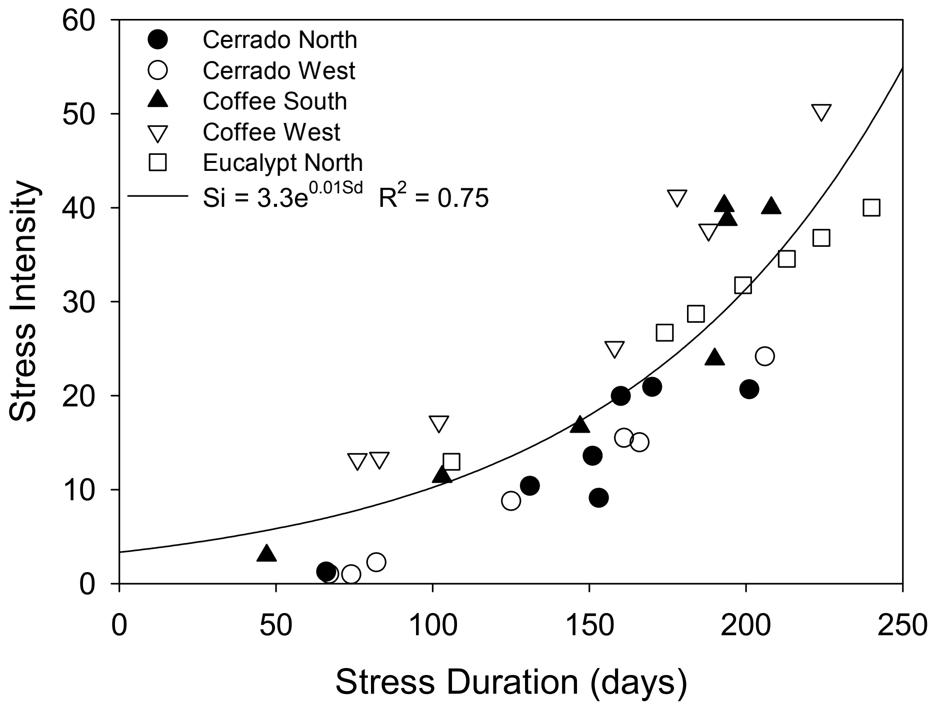

Figure 8 – Relationship between stress intensity (Si) and stress duration (Sd) in the landscape of Minas Gerais, southeast Brazil, based in the observations of cerrado in the north (●) and in the west (○) of Minas Gerais, for coffee in the south (▲) and west (▽) of Minas Gerais and eucalypt in the north of Minas Gerais (☐).

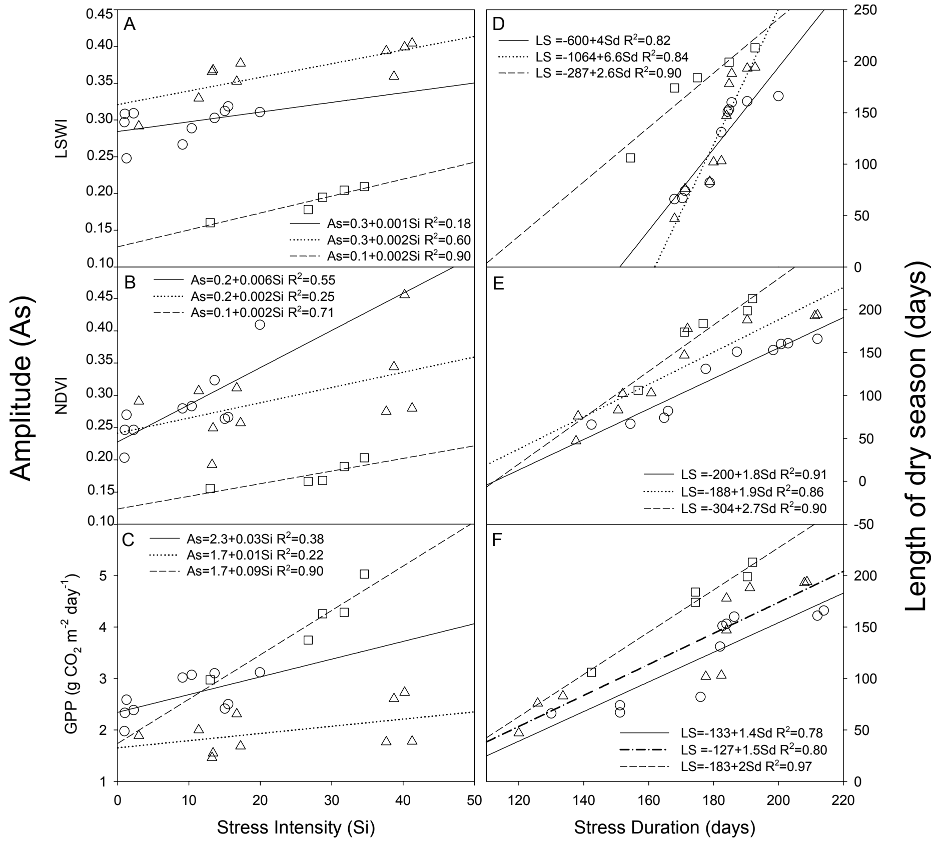

Figure 9 - The relationships between stress intensity (Si) and amplitude of seasons (As) of remote sensed vegetation indices: (A) LSWI, (B) NDVI and (C) GPP. And relationships between the stress duration (Sd) and the length of the dry season (LS) of remote sensed vegetation indices (D) LSWI, (E) NDVI and (F) GPP observed for cerrado (O, —), coffee (△····) and eucalypt (☐ ---), in the landscape of Minas Gerais, southeast Brazil.

6 DISCUSSION

It is suggested that climatic change is going to affect directly and indirectly the functioning and structure of ecosystems, although regional climatic variations make the assessment of vulnerability on a regional level difficult (Chartzoulakis & Psarras, 2005; Tjoelker & Zhou, 2007). Aiming to give an initial step towards the vulnerability assessment of the landscape of Minas Gerais to global changes, we proposed an exercise based on ecosystem functionality and drought stress. The proposed exercise was composed of a procedure based on functional responses at the leaf and ecosystem levels to soil water availability. The objective was to use these variables to study functional sensitivity and from this analysis derive indices and thresholds that would represent the risk levels to the ecosystem functioning.

An important goal of our procedure was the definition of the state of the environmental variable able to characterize vulnerability indices. Since over the past decade, much progress has been made in experimental research and long-term observational studies to characterize and quantify the effects of drought duration and magnitude in limiting the functional process of plants at diverse levels, from leaf (Chaves, 1991; Chaves et al., 2002; Lawlor & Cornic, 2002) to landscape (Rambal et al., 2003; Praxedes et al., 2006), we searched for relations of leaf and canopy functioning with a parameter related to soil water availability.

The relative soil water availability was used as the risk factor because it summarizes the variability in the precipitation regime, evapotranspiration rates and energy balance. These environmental drivers affect the patterns of plant growth and competition, modifying the ecosystem structure and dynamic processes. Such changes should directly impact the carbon budget and the ability of ecosystems to use water efficiently (Kosugi et al., 2006; Potts et al., 2006). Additionally, there is a co-regulation of diverse factors affecting the ecosystems functioning (such as fires, light, heat waves, nutrient availability and high CO_2 concentrations) by the soil moisture (Law et al., 2000; Rosenzweig et al., 2004; Lin, 2007; Hulme, 2005; Suttle et al., 2007; Harpole et al., 2007). To work with only one forcing factor, which integrate other drivers and vegetation characteristics, is also a positive point from the perspective of simulation modeling and vulnerability assessment.

As discussed by Rambal et al. (2003), the main limitation in using this kind of information would be the definition of the lower limit of soil water content, because this is species dependent. In the case of the deep-rooted tree species, it is difficult to measure accurately how much water is available for the plant in the whole profile, and how the importance of the water stored would be to the control of the stomatal conductance on leaf gas exchange (Baldocchi et al., 2004). In spite of the limitations in using RWC as the only variable to describe the functioning at leaf and canopy level in relation to environment, our results suggested that the three studied ecosystems in Minas Gerais showed their functioning limited by soil water availability.

The correlations indicated that most of the variation in the leaf physiology and ecosystem functioning could be explained by the variation of the soil moisture along the year. Moreover, the three ecosystems showed reduction of physiological activities when the water availability decreases to 70% of the maximum capacity of water storage. This threshold of RWC was also observed by Rambal et al. (2003) in mature *Quercus ilex* ecosystem in the Mediterranean basin. Some Brazilian studies corroborate with the observations made in the ecosystems of Minas Gerais, showing that the major factor limiting ecosystem functioning is the soil water availability (Miranda et al., 1997; Araujo et al., 2002; Silva et al., 2004; Silva et al., 2007).

At the leaf level, drought stress is acknowledge for the stomatal control of assimilation, by restricting the supply of CO_2 to photosynthetic metabolism (Castrillo, 1992; Pinheiro et al., 2001; Simioni et al., 2004 among others). Whereas other studies suggest that photosynthesis may be more directly limited by non-stomatal factors, particularly via a direct effect of drought associated to high temperatures on the ATP synthase, thus leading to restricted photosynthetic rates by the ATP supply, as cited by Lawlor & Cornic (2002). At the ecosystem level, there is consent that the plant response to water availability is complex but often leads to decrease in biomass accumulation and production due to a decrease in the leaf photosynthesis (Hutley et al., 2000; Hutley et al., 2001; Ichii et al., 2007). Therefore, the knowledge on the adjustment of stomata in water and carbon exchanges could be the starting point for the comprehension of the vegetation responses to water availability and also to the up and downscaling drought effects through time and space. From this point of view, our exercise indicated directions and values for the development of simulation models as well as for studies related to the vulnerability of plant physiology and production to drought.

The results also enabled scaling procedures, by equaling two equations in function of RWC, and then describing variables of the ecosystem level in function of leaf traits or, inversely, describing leaf traits in function of remote sensed indices. A similar approach was successfully showed by Rambal et al. (2003). This procedure takes into account the functional relationships controlling ecosystem fluxes at the leaf and at the ecosystem level. Although such an approach is not mechanistic, because it does not link environmental factors with stomatal functioning at the biochemical level, it has a character based on sensitivity that could make it useful for the interpretation of field observations, prediction of both conductance and gross assimilation at the ecosystem level, remote sense prediction of leaf characteristic and modeling efforts (Jarvis, 1995). On the whole, and in spite of the simplifying assumptions used in the representation of the ecosystem and leaf level, these equations could be useful for predicting interactions between coffee, eucalypt and cerrado functioning with the environment and for interpreting vulnerability at the landscape level.

Although we did not directly study landscape properties affected by ecosystem functioning, we can assume that the landscape vulnerability is supported on the interrelations among ecosystems, establishing landscape dynamics. These interrelations are dependent on diverse factors conditioning the normal regional characteristics (fire occurrence, anthropogenic pressures, primary production, competition, litter deposition, mass and energy fluxes, hydrology, biodiversity, land cover structure among others) and imbalances in these properties, due to perturbations in one ecosystem, could affect all the landscape dynamics. In the next steps in this research, our intention is to work with spatially explicit, mechanistic models, based on the present results to simulate landscape dynamics using future climate scenarios. We also would implement variables related to feedback responses of vegetation on the atmosphere, land cover changes and fire regime approaches in the vulnerability assessment. This would allow the prediction of ecosystems structure and functioning in the future, supplying basic information necessary to the establishment of mitigation strategies to withstand the negative impacts forecasted with the ongoing climate trends over the landscape.

7 REFERENCES

ARAUJO, A. C.; NOBRE, A. D.; KRUIJT, B.; ELBERS, J. A.; DALLAROSA, R.; STEFANI, P.; VON RANDOW, C.; MANZI, A. O.; CULF, D. A.; GASH, J. H. C.; VALENTINI, R.; KABAT, P. Comparative measurements of carbon dioxide fluxes from two nearby towers in a central Amazonian rainforest: the Manaus LBA site. **Journal of Geophysical Research**, Washington, v. 107, n. 20, p. 80-90, Sept./Oct. 2002.

BALDOCCHI, D. D.; XU, L.; KIANG, N. How plant functional type, weather, seasonal drought, and soil physical properties alter water and energy fluxes of an oak-grass savanna and an annual grassland. **Agricultural and Forest Meteorology**, Amsterdam, v. 123, n. 1-2, p. 13-39, May 2004.

CASTRILLO, M. Sucrose metabolism in bean plants under water deficit. **Journal of Experimental Botany**, Oxford, v. 43, n. 257, p. 1557 – 1561, Dec. 1992.

CHARTZOULAKIS, K.; PSARRAS, G. Global change effects on crop photosynthesis and production in Mediterranean: the case of Crete, Greece. **Agriculture, Ecosystems and Environment**, Amsterdam, v. 106, n. 2-3, p. 147–157, Apr. 2005.

CHAVES, M. M.; PEREIRA, J. S.; MAROCO, J.; RODRIGUES, M. L.; RICARDO, C. P. P.; OSÓRIO, M. L.; CARVALHO, I.; FARIA, T.; PINHEIRO, C. How plants cope with stress in field. Photosynthesis and growth. **Annals of Botany**, London, v. 89, p. 907 – 916, June 2002. Special.

CHAVES. M. M. Effects of water deficits on carbon assimilation. **Journal of Experimental Botany**, Oxford, v. 42, n. 234, p. 1 – 16, Jan. 1991.

HARPOLE, W. S.; POTTS, D. L.; SUDING, K. N. Ecosystem responses to water and nitrogen amendment in a California grassland. **Global Change Biology**, Oxford, v. 13, n. 11, p. 2341-2348, Nov. 2007

HULME, P. E. Adapting to climate change: is there scope for ecological management in the face of a global threat?. **Journal of Applied Ecology**, Cambridge, v. 42, n. 5, p. 784 – 794, Oct. 2005.

HURTT, G. C.; MOORCROFT, P. R.; PACALA, S. W.; LEVIN, S. A. Terrestrial models and global change: challenges for the future. **Global Change Biology**, Oxford, v. 4, p. 581 - 590; June 1998.

HUTLEY, L. B.; O'GRADY, A. P.; EAMUS, D. Evapotranspiration from eucalypt open-forest savanna of Northern Australia. **Functional Ecology**, Oxford, v. 14, n. 5, p. 183-194, June 2000.

HUTLEY, L. B.; O'GRADY, A. P.; EAMUS, D. Monsoonal influences on evapotranspiration of savanna vegetation of northern Australia. **Oecologia**, New York, v. 126, n. 3, p. 434–443, Feb. 2001.

ICHII, K.; HASHIMOTO, H.; WHITE, M. A.; POTTER, C.; HUTYRA, L. R. HUETE, A. R.; MYNENI, R. B.; NEMANI, R. R. Constraining rooting depths in tropical rainforests using satellite data and ecosystem modeling for accurate simulation of gross primary production seasonality. **Global Change Biology**, Oxford, v. 13, n. 1, p. 67–77, Jan. 2007.

JARVIS, P. G. Scaling processes and problems. **Plant, Cell and Environment**, Oxford, v. 18, n. 10, p. 1079–1089, Oct. 1995.

JÖNSSON, P.; EKLUNDH, L. Seasonality extraction by function fitting to time-series of satellite sensor data. **IEE Transactions on Geoscience and Remote Sensing**, New York, v. 40, n. 8, p. 1824-1832, Aug. 2002.

JÖNSSON, P.; EKLUNDH, L. TIMESAT - a program for analyzing time-series of satellite sensor data. **Computers & Geosciences**, Oxford, v. 30, n. 8, p. 833-845, Oct. 2004.

KICKLIGHTER, D. W.; BRUNO, M.; DONGES, S.; ESSER, G.; HEIMANN, M.; HELFRICH, J.; IFT, F.; JOOS, F.; KADUK, J.; KOHLMAIER, G. H.; McGUIRE, A. D.; MELILLO, J. M.; MEYER, R.; MOORE III, B.; NADLER, A.; PRENTICE, I. C.; SAUF, W.; SCHLOOS, A. N.; SITCH, S.; WITTENBERG, U.; WURTH, G.; A firt-order analysis of the potential role of CO_2 fertilization to affect the global carbon budget: a comparizon of four terrestrial biosphere models. **Tellus**, Copenhagen, v. 51, n. 2, p. 343-366, Apr. 1999.

KOSUGI, Y.; TAKANASHI, S.; MATSUO, N.; TANAKA, K.; TANAKA, H. Impact of leaf physiology on gas exchange in a Japanese evergreen broad-leaved forest. **Agricultural and Forest Meteorology**, Amsterdam, v. 139, n. 3-4, p. 182–199, Oct. 2006.

LAW, B. E.; WARING, R. H.; ANTHONI, P. M.; ABER, J. D. Measurements of gross and net ecosystem productivity and water vapour exchange of a *Pinus ponderosa* ecosystem, and an evaluation of two generalized models. **Global Change Biology**, Oxford, v. 6, n. 2, p. 155-168, Feb. 2000.

LAWLOR, D. W.; CORNIC, G. Photosynthetic carbon assimilation and associated metabolism in relation to water deficits in higher plants. **Plant, Cell and Environment**, Oxford, v. 25, n. 2, p. 275–294, Feb. 2002.

LI, P.; BOHNERT, H. J.; GRENE, R. All about FACE - plants in a high-[CO_2] world. **Trends in Plant Science**, London, v. 12, n. 3, p.87-89, Mar. 2007.

LIN, B. B. Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. **Agricultural and Forest Meteorology**, Amsterdam, v. 144, n. 1-2, p. 85–94, May 2007.

LUERS, A. L.; LOBELL, D. B.; SKLAR, L. S.; ADDAMS, C. L.; MATSON, P. A. A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico. **Global Environmental Change**, Oxford, v. 13, n. 4, p. 255–267, Dec. 2003.

METZGER, M. J.; ROUNSEVELL, M. D. A.; ACOSTA-MICHLICK, L.; LEEMANS, R.; SCHRÖTER, D. The vulnerability of ecosystem services to land use change. **Agriculture, Ecosystems and Environment**, Amsterdam, v. 114, n. 1, p. 69–85, May 2006.

MIRANDA, A. C.; MIRANDA, H. S.; LLOYD, J.; GRACE, J.;FRANCEY, R. J.; MCINTYRE, J. A.;MEIR, P.; RIGGAN, P.; LOCKWOOD, R.; BRASS, J. Fluxes of carbon, water and energy over Brazilian cerrado: an analyses using eddy covariance and stable isotopes. **Plant, Cell and Environment**, Oxford, v. 20, n. 3, p. 315-328, Mar. 1997.

NEMANI, R. R.; KEELING, C. D.; HASHIMOTO, H. et al. Climate driven increases in global terrestrial net primary production from 1982 to 1999. **Science**, Washington, v. 300, n. 5625, p. 1560–1563, June 2003.

NIINEMETS, U. Global-scale climatic controls of leaf dry mass per area, density, and thickness in trees and shrubs. **Ecology**, Washington, v. 82, n. 2, p. 453–469, Feb. 2001.

NIYOGI, D.; XUE, Y. Soil moisture regulates the biological response of elevated atmospheric CO_2 concentrations in a coupled atmosphere biosphere model. **Global and Planetary Change**, Amsterdam, v. 54, n. 1-2, p. 94–108, Nov. 2006.

PINHEIRO, C.; CHAVES, M. M.; RICARDO, C. P. Alterations in carbon and nitrogen metabolism induced by water deficit in the stems and leaves of *Lupinus albus* L.. **Journal of experimental Botany**, Oxford, v. 52, n. 358, p. 1063 – 1070, May 2001.

POTTS, D. L.; HUXMAN, T. E.; CABLE, J. M.; ENGLISH, N. B.; IGNACE, D. D.; EITS, J. A.; MASON, M. J.; WELTZIN, J. F.; WILLIAMS, D. G. Antecedent moisture and seasonal precipitation influence the response of canopy-scale carbon and water exchange to rainfall pulses in a semi-arid grassland. **New Phytologist**, Oxford, v. 170, n. 4, p. 849–860, 2006.

PRAXEDES, S. C.; DaMATTA, F. M.; LOUREIRO, M. E.; FERRÃO, M. A. G.; CORDEIRO, A. T. Effects of long-term soil drought on photosynthesis and carbohydrate metabolism in mature robusta coffee (*Coffea canephora* Pierre var. kouillou) leaves. **Environmental and Experimental Botany**, Oxford, v. 56, n. 3, p. 263–273, July 2006.

RAMBAL, S. The differential role of mechanisms for drought resistance in a Mediterranean evergreen shrub: a simulation approach. **Plant, Cell and Environment**, Oxford, v. 16, n. 1, p. 35–44, Jan. 1993.

RAMBAL, S.; OURCIVAL, J. M.; JOFFRE, R.; MOUILLOT, F.; NOUVELLON, Y.; REICHSTEIN, M.; ROCHETEAU, A. Drought controls over conductance and assimilation of a Mediterranean evergreen ecosystem: scaling from leaf to canopy. **Global Change Biology**, Oxford, v. 9, n. 12, p. 1813 – 1824, Dec. 2003.

REICH, P. B.; TURNER, D. P./;BOLSTAD, A. P.. An approach to spatially distributed modeling of net primary production (NPP) at the landscape scale and itsa in validation of EOS NPP products. **Remote Sensing of Environ**ment, New York, v. 70, n. 1, p. 69–81, Oct. 1999.

ROSENZWEIG, C.; STRZEPEK, K.M.; MAJOR, D.C.; IGLESIAS, A.; YATES, D.N.; McCLUSKEY, A.; HILLEL, D. Water resources for agriculture in a changing climate: international case studies. **Global Environmental Change**, Oxford, v. 14, n. 4, p. 345–360, Dec. 2004.

RUIZ, H. A.; FERREIRA, G. B.; PEREIRA, J. B. M. Estimativa da capacidade de campo de latossolos e neossolos quartzarênicos pela determinação do equivalente de umidade. **Revista Brasileira de Ciência do Solo**, Viçosa, MG, v. 27, n. 2, p. 389-393, mar./abr. 2003.

SANTOS, S. N. M.; COSTA, M. H. A simple tropical ecosystem model of carbon, water and energy fluxes. **Ecological Modelling**, Amsterdam, v. 176, n. 3-4, p. 291-312, Sept. 2004.

SCHOLZ, F. G.; BUCCI, S. J.; GOLDSTEIN, G.; MEINZER, F. C.; FRANCO, A. C.; MIRALLES-WILHELM, F. Biophysical properties and functional significance of stem water storage tissues in neotropical savanna trees. **Plant, Cell and Environment**, Oxford, v. 30, n. 2, p. 236- 248, Feb. 2007.

SHAVER, R. G.; CANADELL, J.; CHAPIN III, F. S.; GUREVITCH, J.; HARTE, J.; HENRY, G.; INESON, P.; JONASSON, S.; MELILLO, J.; PITELKA, L.; RUSTAD, L. Global warming and terrestrial ecosystems: a conceptual framework for analysis. **BioScience**, Washington, v. 50, n. 10, p. 871-882, Oct. 2000.

SILVA, E. A.; DaMATTA, F. M.; DUCATTI, C.; REGAZZIC, A. J.; BARROSA, R. S. Seasonal changes in vegetative growth and photosynthesis of arabic coffee trees. **Field Crops Research**, Amsterdam, v. 89, n. 2-3, p. 349–357, Oct. 2004.

SILVA, M. R.; RIBEIRO, M. G.; CENTENO, J. A. S. Monitoramento de estiagens com imagens MODIS. SIMPÓSIO BRASILEIRO DE SENSORIAMENTO REMOTO, 13., 2007, Florianópolis. **Anais...** Florianópolis: INPE, 2007. p. 6229-6236.

SIMIONI, G.; LE ROUX, X.; GIGNOUX, J.; WALCROFT, A. Leaf gas exchange characteristics and water- and nitrogen-use efficiencies of dominant grass and tree species in a West African savanna. **Plant Ecology**, Dordrecht, v. 173, n. 2, p. 233 – 246, Aug. 2004.

SUTTLE, K. B.; THOMSEN, M. A.; POWER, M. E. Species interactions reverse grassland responses to changing climate. **Science**, Washington, v. 315, n. 5872, p. 640–642, Feb. 2007.

TJOELKER, M. G.; ZHOU, X. The many faces of climate warming. **New Phytologist**, Cambridge, v. 176, n. 4, p. 739–742, 2007.

WATSON, R. T.; NOBLE, I.R.; BOLIN, B.; RAVINDRANATH, N. H.; VERARDO, D. J.; DOKKEN, D. J. (Ed.). **Land Use, Land use Change and Forestry. A Special Report of the Intergovernmental Panel on Climate Change** (IPCC). Cambridge: Cambridge University, 2000.

WRIGHT, I. J.; REICH, P. B.; CORNELISSEN, J. H. C.; FALSTER, D. S.; GARNIER, E.; HIKOSAKA, K.; LAMONT, B. B.; LEE, W.; OLEKSYN, J.; OSADA, N.; POORTER, H.; VILLAR, R.; WARTON, D. I.; WESTBOY, M. Assessing the generality of global leaf trait relationships. **New Phytologist**, Cambridge, v. 166, n. 2, p. 485–496, May 2005a.

WRIGHT, I. J.; REICH, P. B.; CORNELISSEN, J. H. C.; FALSTER, D. S.; GROOM, P. K.; HIKOSAKA, K.; LEE, W.; LUSK, C. H.; NIINEMETS, U.; OLEKSYN, J.; OSADA, N.; POORTER, H.; WARTON, D. I.; WESTBOY, M. Modulation of leaf economic traits and trait relationships by climate. **Global Ecology and Biogeography**, Oxford, v. 14, n. 5, p. 411-421, Sept. 2005b.

CHAPTER VI

Conclusions

1 RESEARCH OVERVIEW AND OUTCOMES

Over the course of this study, one key subject was to give an initial step towards the assessment of the vulnerability of the landscape of Minas Gerais, southeast Brazil, to global changes by the establishment and analysis of a database composed by three axes: landscape properties, vegetation functioning and environmental variables. Another key concern was to work in an integrative approach across disciplines, across temporal and spatial scales, and across levels of organization, considering the complex interactions among the different themes related to the effects of global changes over the terrestrial ecosystems (Figure 1). This procedure included analysis of time-series and correlation of variables to describe ecophysiological responses generally related to site-specific, annual seasonality and inter-annual non-standard weather conditions, such as the ones caused by El Niño events.

The evaluation of near-past, present and future weather on Minas Gerais indicated that the occurrence of drought would increase in the future. As a result, most of the analytic procedure was dedicated to examine the direct effects of temporal and spatial water limitation on landscape properties from functional characteristics. Thus, we proposed a bottom-up approach to summarize this complexity and to give insights on landscape vulnerability. This procedure was applied in three case studies: coffee plantations, eucalypt forests and natural cerrado ecosystem in the north, south and west of Minas Gerais.

In general, the analysis indicated that the characteristics of ecosystem functioning, land cover structure and fire regime were largely influenced by water availability on annual and inter-annual scales. Furthermore, the differences in the weather characteristics among the studied sites in Minas Gerais conditioned typical spatial patterns of landscape response to drought. We could observe that most of the variability in the analyzed ecophysiological characteristics must result from the remarkable effect of the dry season on all levels of organization. Such observations point that the annual-to-decadal and the micro to meso-scale landscape responses to global changes in Minas Gerais would largely depend on the seasonal drought effects over ecosystem functioning.

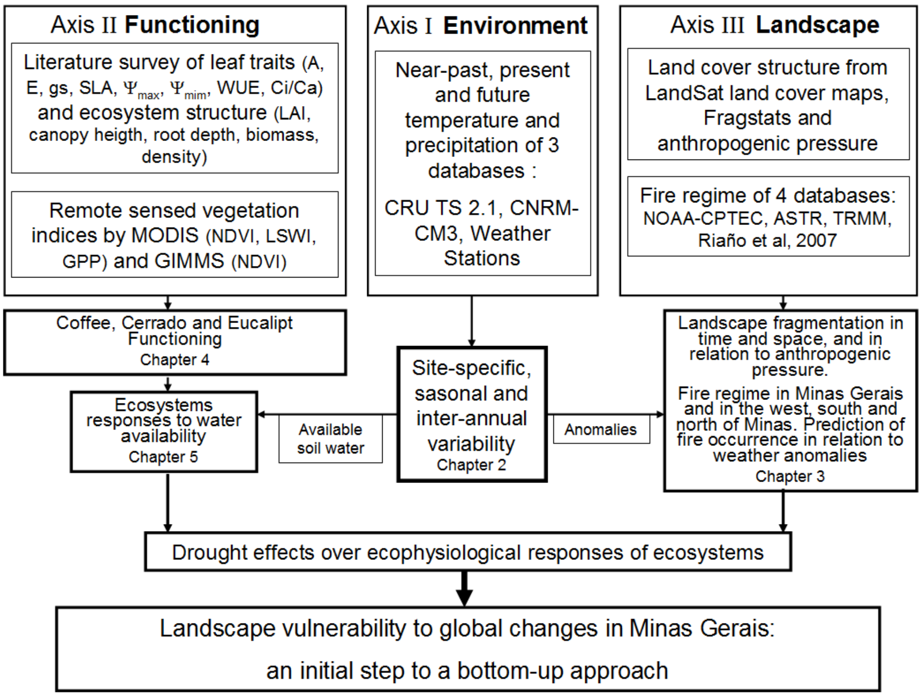

Figure 1 – Representation of the database and of the procedure used to analyze the three axes of datasets in function of seasonal, inter-annual and site-specific water availability and weather anomalies influencing the variability in the responses of ecosystems, aiming to assess the landscape vulnerability in Minas Gerais in a bottom-up approach.

The sensitivity of the functional responses of the three ecosystems to space-time moisture availability provided a summary of the sort of information that could be used to understand the relationships among leaf-to-ecosystem as well as to the adjustments of leaf and canopy parameters to environmental perturbations. These results could be employed to assess biophysical aspects of each ecosystem, to improve the representations of the processes related to carbon assimilation and water transport and in scaling exercises, using remotely sensed observations related to leaf functioning. This is positive in the proposed approach for the assessment of landscape vulnerability by ecophysiological parameters as well as for the perspectives of further parameterization and validation of mechanistic process-based simulation models to the Minas Gerais landscape.

Noticeable effects of the dry season over ecophysiological parameters of the studied ecosystems were the generalized reduction in the values of the leaf traits and remotely sensed indices. At the landscape level, the reduction of precipitation rates, together with the increasing temperatures at the end of the dry season conditioned the maximum fire occurrence in all the area of Minas Gerais. However, the fire frequency in the north of Minas Gerais was higher than in the other studied regions. Moreover, we observed that fire spots concentrated in the borders of the areas under high and low anthropogenic pressure and that the biomass burning tends to increase with the weather trends into the next decades. Those observations could suggest that the landscape of Minas Gerais could be a source of CO_2 for the atmosphere in the future if the duration and severity of seasonal drought increases in the future.

In summary, the construction of a database of space-time information related to land cover and fire regime, weather characteristics, vegetation and soil maps, remotely sensed vegetation indices and leaf traits was an initial step toward the study of the variety of the effects of climatic changes over landscape dynamics in Minas Gerais. This preliminary information was worked together with an integrative procedure for the study of the complex effects of climatic changes over ecosystems functioning and landscape vulnerability. From these perspectives, our results propitiated some advances in the understanding of the relationships of processes from leaf level to landscape, relating weather variability, as well as in the spatial distribution of these features. These advances have come from the relationships at a range of spatial and temporal scales, especially in those which remote sensing data was combined with information from other sources.

2 LIMITATION OF THE ANALYSIS

The results reported in this study depended on many assumptions built into the database construction and analytic procedure that should to be considered before any implications. Limitations can be associated with deficient knowledge and representations of the physical processes related to weather variability in function of global climatic models, the simplifications and assumptions in the regression equations and dataset approaches, and also the inherent variability of remote sensed data and the internal and inter-dataset variability.

The first limitation implied on the use of global datasets to describe the variability of temperature and precipitation at local scale. The wide range of uncertainties inherent in downscaling these datasets to the regional level lies in the restricted ability to describe and predict change in the inter-annual and seasonal patterns of weather variability or in the frequency of extreme episodes, which can be just as, or more important in determining vulnerability as average temperature and precipitation. Moreover, the gap of observational weather datasets and site-specific micrometeorological information limited our analysis. The available data from weather stations is restricted to air temperature and precipitation and is in a short-term series, some of which may be missing at any given time and which are unlikely to reflect actual or recent-past weather variability. Information related to solar radiation is available from an 8 year time-series, from a network of automatic weather stations.

Considering the scale of the characteristics under study, site-specific micrometeorological information should be implemented in our datasets. There is an evident gap of adequate observational data of ecosystem functioning and structure, as well as biophysical characteristics at the site level in Minas Gerais. The few available data consisted of scattered and isolated studies. This would require an effort of the diverse research groups in Minas Gerais to work together and put an observational network in practice or transect approaches on the main ecosystems in the state.

A second important limitation of this study were the regression equations generated from function equations of data from different sources and diverse space-time scales. Moreover, some of the regression equations showed restrictions due to the numerical approximations of the parameters. In spite of these restrictions, the results could mark significant progress in our understanding of how the leaf traits are related to ecosystem functioning and how weather variability may affect the processes at both levels.

At the functional axis, the main limitation in our approach was the literature information, obtained by extraction of average values from diverse study conditions. In relation to cerrado ecosystem, the restriction was not to consider the functional groups, because information on fluxes, litter formation and root system at this level is under-represented in the literature, in spite of their great significance for carbon storage, energy balance and their responses to seasonal changing in moisture supply. Another constraint in the functional information could be related to the inherent limitation of remote sensed indices, due to the still unclear understanding of the critical factors controlling the remote sensed signatures in the ecosystems of Minas Gerais at the biophysical, biochemical and ecological levels. The validation of remotely sensed signatures of each ecosystem could be solved by field experiments and observations.

Due to those limitations, the insights on landscape vulnerability and the ecophysiological responses to weather variability in Minas Gerais shown here should be cautiously considered. Although some results were satisfactory from some perspectives, predictions of the entire complexity of ecosystem responses and landscape vulnerability should include long-term data collection and monitoring; studying interactions across spatial scales, evaluating interactions among different ecosystems to gain a better understanding of ecosystem function and the global changes. This could be approached by experimental efforts, field observations and by simulations with process-based, mechanistic and spatially explicit models. Future research must be performed to analyze those relationships, including all the aspects related to ecosystem functioning, anthropogenic activities, fire regime, land cover and use. Furthermore, the feedback responses of vegetation to the atmosphere in relation to weather variability should be considered in future approaches.

3 VULNERABILITY OF THE LANDSCAPE OF MINAS GERAIS TO GLOBAL CHANGES: FINAL REMARKS AND PERSPECTIVES

In summary, the proposed procedure for the assessment of the landscape vulnerability consisted in restricting only to drought the perturbation factors affecting ecosystems responses to environment, to predict responses driven by weather datasets that were downscaled to impacts at the leaf level (a top-down approach). Then we redirected the analysis from the leaf to the landscape level, where risks and thresholds of water availability affecting normal functioning were the basic features in the vulnerability assessment (a bottom-up approach). However, as diverse types of impacts are recognized and the interactions between local, regional, and global scales becomes more documented, skillful forecasts of the ecosystems responses and vulnerability becomes an increasingly challenging task. This challenge requires a greater focus on the assessment of the social and environmental vulnerabilities, since impacts on landscape extend far beyond mean temperature and precipitation, and other perturbations, such as land use changes and ecological interactions can have important effects on ecosystem functioning and landscape dynamics.

For this reason, we propose a more complex framework for vulnerability assessment, where functioning is still place-based and has a bottom-up perspective (Figure 2). However, the effects over ecophysiological responses have other forcings. Additionally, in this framework the challenge is to use mechanistic simulation models and field observations to interrelate and determine thresholds at which negative effects of drought represent only one threat and occur associated with the other forcings such as land-surface dynamics; changes in agricultural practices, such as irrigation and other management; animal, pathogen and insect dynamics; fire occurrence; interaction among plant species and soil dynamics.

The interaction among species may play important roles in shaping the ecophysiological responses, as competition for water, light and nutrients can determine allocation patterns and resilience capacity. Under certain circumstances, the patterns of species interaction have important implications on the regional fluxes of mass and energy. For this reason factors such as dispersal ability and competition for nutrients and water, insect herbivory and plant diseases will need to be implemented and coupled with functional properties in future approaches. This would make possible a better interpretation of the results and patterns of landscape vulnerability that we observed in this study.

Another important consideration within the framework of possibilities assessed in the present study is the changing picture of land use, and its interactions with climate change effects, ecosystems functioning and fire occurrence. This is a more difficult issue to be implemented, since it depends on anthropogenic pressures. Such variables are clearly important and will certainly define the fine-scale limitations on the functional patterns of natural and managed ecosystems on the landscape. One approach to assess and include the social component in the framework is to question the community about their current knowledge and reaction to effects due to impacts of the existing weather conditions, and this way determine their risk threshold.

Further, we will need to better develop our understanding of how information on the leaf, canopy, ecosystem and biogeochemical fluxes might be used together in scaling exercises to generate long-term predictions, based on relative sensitivity and adaptation strategies to climate change. We also need improved models of the temporal and spatial responses of ecosystems to environment, because it is increasingly clear that long-term responses to warming and increased CO_2 may differ greatly among ecosystems and possible feedback on the atmosphere is still uncertain. For the construction of such models, a broader array of experiments in contrasting ecosystem types into the regional landscape is needed; including both whole system manipulations and more focused experimental treatments at the leaf level. Also needed are the long-term monitoring of weather, and the development of research networks that will allow spatial extrapolation and validation of predictions based on intensive experimental studies.

Our results and this framework for analysis, comparison, and prediction of ecosystem responses to environment is only a-part-of-the-whole in the climate change research in Minas Gerais. For now, the principal applications of this initial step and of this framework, are the statement of the dimensions of complexity of the responses at diverse scales; the integrative approach needed to study the effects of global changes that is not just multidisciplinary, but truly interdisciplinary; the establishment of the main connections between processes; to know the limitations and to point out the necessity of the subsequent studies and, finally, as a reminder of the major constraints on long-term predictions based on relatively small-area and short-term studies. With this bottom-up perspective, the distribution of impacts across ecosystems in Minas Gerais would be assessed, and objectively confirmed, as a more accurate assessment and prediction of the local impacts of the global changes. We think this could be a more beneficial and realistic approach than seeking to downscale to the local region from global approaches and that this knowledge is an important component of the strategy to understand, simulate, anticipate and, finally, set up strategies to mitigate and/or adapt the potential effects of global changes on ecosystems and socio-economic activities on the Minas Gerais landscape.

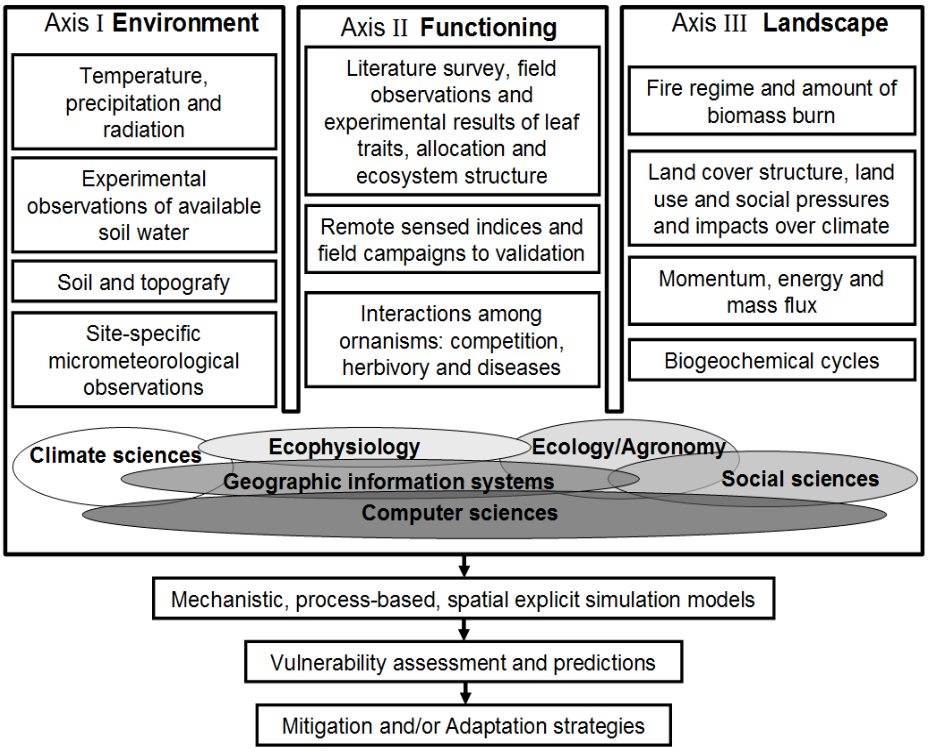

Figure 2 – A framework to analyze and predict the effects of climate changes over landscape dynamics in Minas Gerais.