

MARIANA GONÇALVES DOS REIS

**CARBON, WATER AND ENERGY FLUXES IN EUCALYPTUS
PLANTATIONS AND SAVANNA IN BRAZILIAN TROPICS**

Thesis submitted to the Agricultural Engineering Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae*.

VIÇOSA
MINAS GERAIS – BRAZIL
2018

**Ficha catalográfica preparada pela Biblioteca Central da Universidade
Federal de Viçosa - Câmpus Viçosa**

T

R375c
2018
Reis, Mariana Gonçalves dos, 1989-
Carbon, water and energy fluxes in Eucalyptus plantations
and Savanna in Brazilian tropics / Mariana Gonçalves dos Reis.
– Viçosa, MG, 2018.
xiv, 74 f. : il. (algumas color.) ; 29 cm.

Texto em inglês.

Inclui apêndice.

Orientador: Aristides Ribeiro.

Tese (doutorado) - Universidade Federal de Viçosa.

Referências bibliográficas: f. 57-67.

1. Eucalipto. 2. Evapotranspiração. 3. Cerrados. 4. Água -
Uso. 5. Análise de covariância. 6. Ciclo do carbono
(Bioquímica). 7. Balanço energético (Geofísica).
8. Micrometeorologia. I. Universidade Federal de Viçosa.
Departamento de Engenharia Agrícola. Program de
Pós-Graduação em Engenharia Agrícola. II. Título.

CDO adapt. CDD 22. ed. 634.9118

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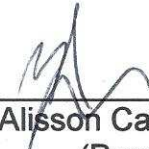
APPROVED: February 27, 2018.


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This thesis is dedicated...

To my parents, Evonete and Jésus,
To my lovely brothers, Daniel and Renato,
To my best friend and love, Elton Alves,
To all professors, friends and family.

*“Não é o que você faz, mas quanto amor você
dedica no que faz que realmente importa”.*
(Madre Teresa de Calcutá)

ACKNOWLEDGMENTS

To God, for being my biggest support all the time. Thank you my Lord, to be my example of humility and love, for giving me peace and wisdom. Thanks for everything, especially for my life and health.

I'm really grateful to my parents Evonete and Jésus, for all teachings, support and dedication to my personal and professional formation. Thank for the love and prayers.

To my brothers Renato and Daniel, my sister-in-law Camila and my lovely goddaughter Paulinha, for all great moments, friendship and partnership. Also thank to my parents-in-law, who always makes me happy and special.

To my beloved Elton Eduardo Novais Alves. Thank you for everything, for be my best friend and companion, for making me happy and complete me with your presence. You are my example of professional dedication, effort and competence.

A special thanks to the Universidade Federal de Viçosa (UFV) for all support, excellent opportunities, great professors and invaluable friendships along these 11 years. Thank you so much UFV!

I would like to thank to Agricultural Engineering Department (DEA), Engineering Agricultural Graduate Program, and Applied Meteorology Graduate Program for all support and opportunity to conduct my thesis.

To National Council for Scientific and Technological Development (CNPq) for the financial support to this research. To Coordination for Improvement of Higher level education (CAPES) for doctoral Sandwich scholarship.

To my advisor, professor Aristides Ribeiro. I'm really grateful for your teachings, friendship, and for all great opportunities you gave me along these almost 10 years. Thank you so much!

To my co-advisors: Dr. Asko Noormets, Dr. Rodolfo Araujo Loos, Dr. Yhasmin Paiva Rody, and Dr. Wagner Luiz Araújo for all help during my doctoral.

I grateful to Fibria Celulose S.A. for financial support as well as for logistical and human recourses. The contributions of all field staff of Fibria are gratefully acknowledged.

To North Carolina State University (NCSU) to all support during my doctoral internship. A special grateful to Dr. Asko Noormets, for all your attention and important teachings, especially in eddy covariance data processing and analysis.

To all friends in USA, specially: Bhaskar Mitra, Suna Morkoc, Wen Lin, Jonathan Furst, Kai Duan, Dennis Hallema, Dr. John King, Erika Cohen, Jeniffer Moore, Dr. Steven McNulty, Yuan Fang, Brenda D'Acunha, Priyanka Manjunatha, Cláudia Alberico. Thanks to share with me invaluable moments during my internship. I'm so glad to meet all of you!

To all friends from my research group, in special: Aylene Ramos, Elias Pedroso, Hugo Thaner, José Darlon, Luiz Felipe, Mariana Magalhães, Marciel Lelis, Marshall Santos, Robert Barbosa and Vitor Hugo. Also, to all students from Applied Meteorology Graduate Program. You are very special to me!

To Aylene Ramos for all teachings and help with Matlab program. You are the best!

To Graça Freitas, you are the best secretary that I ever met. Thank you so much for all help, availability, care and friendship.

To professor Paulo José Hamakawa. For always encourage me to be a better professional.

To Marine and Daniel for great moments lived during the last two years.

Finally, to all professors, friends and family who directly or indirectly contributed to the accomplishment of this work.

BIOGRAPHY

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In March of 2014 initiated the doctorate in Agricultural Engineering Graduate Program (UFV). From April to August, 2017, she was Visiting Scholar at North Carolina State University (NCSU), Raleigh – NC, USA. The thesis has been submitted to the committee in February of 2017, to obtain the *Doctor Scientiae* degree in Agricultural Engineering.

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LIST OF ABBREVIATIONS AND SYMBOLS

ANNs	Artificial Neural Networks
C	CO ₂ concentration
CO ₂	Carbon dioxide
c _p	Specific heat of air
DOY	Day of year
E ₀	Activation energy parameter
EBC	Energy Balance closure
EC	Eddy Covariance
ET	Evapotranspiration
EUC	Eucalyptus ecosystem
EVI	Enhanced Vegetation Index
FAO	Food and Agriculture Organization of the United Nations
F _c	CO ₂ flux
G	Soil Heat Flux
g _c	Canopy Conductance
GPP	Gross Primary Production
H	Sensible Heat Flux
H ₂ O	Water
ha	hectare
Hz	Hertz
IBÁ	Brazilian Tree Industry
IBGE	Brazilian Institute of Geography and Statistics
IPCC	Intergovernmental Panel on Climate Change
IRGA	Infrared Gas Analyzer
LAI	Leaf Area Index
LE	Latent Heat Flux
LUT	Look-up tables
MDV	Mean diurnal variation
MODIS	Moderate Resolution Imaging Spectrodiometer
n	Number of observations
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index

NEE	Net Ecosystem Exchange
NEE _{mod}	NEE modeled values
NEE _{obs}	NEE measurements values
NEP	Net Ecosystem Production/Productivity
NR	Nonlinear Regression
P	Atmospheric Pressure
PAR	Photosynthetically Active Radiation
PPFD	Photosynthetic Photon Flux Density
q	Water vapor mixing ratio
qc	Quality control
R _d	Universal gas constant specific for dry air
R _{eco}	Ecosystem Respiration
Re _{co.ref}	Ecosystem base respiration at 15 °C
Rg	Solar Radiation
RH	Relative Humidity
Rn	Net Radiation
R _w	Universal gas constant specific for water vapor
SAV	Savanna ecosystem
SD	Standard Deviation
SWC	Soil water content
T ₀	Air temperature parameter
T _{air}	Air temperature
T _{soil}	Soil temperature
TOB1	Table Oriented Binary Format 1
TOB3	Table Oriented Binary Format 3
T _{ref}	Temperature sensitivity
u	Horizontal wind speed (fluctuating velocity component in x direction)
u	Gap-filling uncertainty
u*	Friction velocity
u* _{th}	Friction velocity threshold
v	Horizontal wind speed (fluctuating velocity component in y direction)
VPD	Vapor Pressure Deficit
w	Vertical wind speed (fluctuating velocity component in z direction)

WPL	Webb, Pearman and Leuning theory
ws	Wind speed
WUE	Water-Use Efficiency
WUE _i	Intrinsic Water-Use Efficiency
yr	Year
β	Bowen Ration
λ	Latent heat of vaporization for water
ρ	Dry air density

ABSTRACT

REIS, Mariana Gonçalves dos, D.Sc., Universidade Federal de Viçosa, February, 2018. **Carbon, water and energy fluxes in eucalyptus plantations and savanna in Brazilian Tropics**. Advisor: Aristides Ribeiro. Co-advisors: Rodolfo Araujo Loos and Wagner Luiz Araújo.

In Brazil the eucalyptus's plantations area is higher than 5.7 million ha, stand out for Mato Grosso do Sul State (MS) which had led the expansion over the last five years (2011-2016). Most of these areas in MS are into a native savanna forest replaced by degraded pasture and annual crops in the past. Therefore, the effect of this land-cover change on regional carbon and water cycle remains unclear. Here, it was used the eddy covariance technique, meteorological, soil and plant measurements to explore the environmental dependence of intrinsic water- and radiation efficiencies in two different studies in Brazilian tropics: **First study (1)** reported a full rotation cycle (9 years) of carbon, water and energy fluxes from a clonal *Eucalyptus grandis* plantation. Overall the environmental variables, photosynthetically active radiation (PAR), air temperature (T_{air}), water vapor saturation pressure deficit (VPD), rainfall, and soil water content (SWC) followed seasonal drought and wet conditions. During the 9-years of study, the annual total rainfall ranged between 986 to 1496 mm yr⁻¹, with an average of 1238 mm yr⁻¹. Before the harvest of trees, the eucalyptus forest was a strong carbon sequestration during all years (1-8 years), the annual net ecosystem exchange (NEE) sum increased from -256 to -1515 g C m⁻² yr⁻¹, the annual gross primary production (GPP) sum increased from 2312 to 4059 g C m⁻² yr⁻¹, and the annual ecosystem respiration (Reco) sum increased from 1195 to 2751 g C m⁻² yr⁻¹. The first year after harvest of trees (including site preparation and planting of new trees), the annual sum was NEE = 883, GPP = 1248 and Reco = 2132 g C m⁻² yr⁻¹, indicating a small carbon source for this period. Thus, the total carbon sequestration during a full rotation cycle was 78 t C ha⁻¹. Energy balance ($R_n = LE + H + G$) described typical daily patterns of sensible, latent and soil heat transfer, with maximal fluxes at solar noon. The annual total evapotranspiration (ET) ranged between 837 to 1432 mm yr⁻¹, with an average of 1154 mm yr⁻¹. Patterns in intrinsic water-use efficiency (WUE_i) and canopy conductance (g_s) during the study

matched those variations in leaf area index (LAI), GPP and ET. In conclusion, our results provide an important contribution of carbon, water and energy balance in a full rotation cycle of eucalyptus plantations that can be useful to evaluate land-cover changes for this region and even in other regions of Brazil.

Second study (2) the goal was to compare the differences in carbon, water and energy fluxes between a native Savanna forest (SAV) and eucalyptus plantation (EUC) during December 2012 to August 2013. The daily T_{air} (mean 23 °C), PAR (mean 34 mol m⁻² day⁻¹), and rainfall cumulative (sum 1013.5 mm) were similar among the two ecosystems. In contrast, the daily values of VPD and SWC were lower in SAV than EUC throughout the study period. The sum of NEE (-1136 g C m⁻²) for this period indicates that the ecosystem with EUC is a carbon sink, in contrast, for the SAV ecosystem the sum of NEE (256 g C m⁻²) indicated to be a carbon source ecosystem. Overall, the latent heat flux (LE) dominated the energy balances at both ecosystems, followed by sensible heat flux (H) and soil heat flux (G). The total ET at the SAV ecosystem and EUC ecosystem was estimating as 948 and 1050 mm, respectively. Leaf area index (LAI) in SAV ecosystem varied 3.8 to 1.9 m⁻² m⁻², and in EUC ecosystem varied 4.7 to 3.2 m⁻² m⁻², wet and dry period respectively. In summary, the savanna ecosystem was a weak carbon source from the ecosystem to atmospheric (2.5 t C ha⁻¹), and the eucalyptus ecosystem was a strong carbon sink from the atmosphere to ecosystem (11 t C ha⁻¹) over the study period (9 months). The results indicate that the eucalyptus plantations in savanna biome are well adapted to the environmental conditions and have a good response to variability of climate conditions. In addition, the land-cover change and land use practices from pasture to eucalyptus plantations can help or even restore the biodiversity of savanna biome.

RESUMO

REIS, Mariana Gonçalves dos, D.Sc., Universidade Federal de Viçosa, fevereiro de 2018. **Fluxos de carbono, água e energia em plantios de eucalipto e cerrado nos trópicos brasileiro**. Orientador: Aristides Ribeiro. Coorientadores: Rodolfo Araujo Loos e Wagner Luiz Araújo.

No Brasil, a área com plantações de eucalipto é superior a 5,7 milhões de ha, destacando-se o estado do Mato Grosso do Sul (MS), que liderou a expansão em áreas plantadas nos últimos cinco anos (2011-2016). A maior parte dessas áreas plantadas no estado do MS está em áreas de floresta nativa do Cerrado, que foram substituídas principalmente por pastagens degradadas e culturas anuais no passado. Portanto, os efeitos desta alteração na cobertura do solo, no ciclo regional de carbono e da água ainda não estão compreendidos. Neste contexto, foi usada a técnica de covariância dos vórtices turbulentos, medidas meteorológicas, do solo e da vegetação para explorar as eficiências intrínsecas do uso da água e da radiação em dois diferentes estudos nos trópicos brasileiros: **Primeiro estudo (1)** teve como objetivo avaliar um ciclo completo de rotação (9 anos) de fluxos de carbono e água de uma plantação clonal de *Eucalyptus grandis*. No geral, as variáveis ambientais, radiação fotossinteticamente ativa (PAR), temperatura do ar (Tair), déficit de pressão de vapor de água (VPD), precipitação e o conteúdo de água no solo (SWC) seguiram as condições sazonais de época seca e chuvosa. Durante os 9 anos de estudo, a precipitação total anual variou entre 986 e 1496 mm ano⁻¹, com uma média de 1238 mm ano⁻¹. Antes do corte das árvores, a floresta de eucalipto mostrou-se ser um forte sumidouro de carbono durante todos os anos (1-8 anos), a soma anual da produtividade líquida do ecossistema (NEE) aumentou de -256 para -1515 g C m⁻² ano⁻¹, a soma anual da produção primária bruta (GPP) aumentou de 2312 para 4059 g C m⁻² ano⁻¹, e a soma anual da respiração do ecossistema (Reco) aumentaram de 1195 para 2751 g C m⁻² ano⁻¹. O primeiro ano após o corte das árvores (incluindo a preparação do local e o anovo plantio), a soma anual foi NEE = 883, GPP = 1248 e Reco = 2132 g C m⁻² ano⁻¹, indicando ser fonte de carbono neste período. Assim, o total de carbono sequestrado durante um ciclo completo de rotação foi de 78 t C ha⁻¹. O balanço de energia (Rn = LE + H + G) descreveu padrões diários típicos de transferência de calor sensível, calor latente e fluxo de calor no solo

com fluxos máximos ao meio-dia solar. A evapotranspiração (ET) total anual variou entre 837 e 1432 mm ano⁻¹, com uma média de 1154 mm ano⁻¹. A eficiência intrínseca de uso da água (WUE_i) e a condutância do dossel (g_c) corresponderam as variações do índice de área foliar (IAF), GPP e ET durante o período de estudo. Em conclusão, os nossos resultados forneceram uma importante contribuição dos balanços de carbono, água e energia em um ciclo completo de rotação em plantações de eucalipto que podem ser úteis para avaliar mudanças de cobertura do solo nesta região e até mesmo em outras regiões do Brasil. **Segundo estudo (2)** o objetivo foi comparar as diferenças nos fluxos de carbono, água e energia entre uma floresta nativa de Cerrado (SAV) e em plantações de eucalipto (EUC) durante o período de dezembro de 2012 a agosto de 2013. Os valores diários da Tair (média de 23 °C), PAR (média de 34 mol m⁻² dia⁻¹) e da precipitação acumulada (soma 1013,5 mm) foram semelhantes entre os dois ecossistemas. Ao contrário, os valores diários de VPD e SWC foram menores no ecossistema da SAV do que no ecossistema EUC ao longo do período estudado. A soma da NEE (-1136 g C m⁻²) para este período indica que o ecossistema com EUC é sumidouro de carbono, ao contrário, para o ecossistema com SAV a soma da NEE (256 g C m⁻²) indicou ser um ecossistema fonte de carbono. No geral, o fluxo de calor latente (LE) dominou o balanço de energia em ambos os ecossistemas, seguido pelo fluxo de calor sensível (H) e pelo fluxo de calor do solo (G). A evapotranspiração total na SAV e no EUC foi estimada em 948 e 1050 mm, respectivamente. O índice de área foliar (LAI) no ecossistema SAV variou de 3,8 a 1,9 m² m⁻² e no ecossistema EUC variou de 4,7 a 3,2 m² m⁻², no período úmido e seco, respectivamente. Considerando o período estudado, o cerrado foi fonte de carbono do ecossistema para a atmosfera (2,5 t C ha⁻¹), já o plantio de eucalipto foi um forte consumidor de carbono da atmosfera para o ecossistema (11 t C ha⁻¹) ao longo do estudo período (9 meses). Os resultados indicam que as plantações de eucalipto no bioma de savana estão bem adaptadas às condições ambientais e têm uma boa resposta à variabilidade das condições climáticas. Além disso, a mudança da cobertura do solo e as práticas de uso do solo do cultivo com pastagens para plantações de eucalipto podem ajudar ou mesmo restaurar a biodiversidade do bioma de savana.

1. INTRODUCTION

Forests cover about ~4 billion hectares of the earth's land surface (FAO, 2015a). Currently, 291 million ha (~7.2%) of this area have been occupied with planted forest (FAO, 2015a). Planted forest is an important cultivation which reduce the pressure on natural forests by timber industry (Cook et al., 2016; FAO, 2016; Christina et al., 2018). Particularly, fast-growing of eucalyptus species with a short rotation cycle (6 – 8 years) are establishing in many places around the world: Brazil (Binkley et al., 2017; Soares et al., 2017), Europe (Teixeiras, 2017), North America (Crow et al., 2016; Maier et al., 2017), China (Williams, 2017), South Africa (Dube et al., 2017), Australia (Forrester, 2015), Congo (Epron et al., 2013), and Chile (Vargas et al., 2017), among others.

Eucalyptus spp. plantation area reached over 20 million ha in the world (FAO, 2016; Silva et al., 2017; Vargas et al., 2017), mainly in tropical and subtropical regions (Cook et al., 2016; Liu et al., 2017). It is important to mention that the largest area with eucalyptus plantations are in Brazil (IBÁ, 2017; Scolforo et al., 2017), China (Zhang et al., 2016; Liu et al., 2017), and India (Ramanagouda et al., 2010; Silva et al., 2017), respectively. The major factor explaining this fast growth of eucalyptus plantations in these areas is due to high resource use-efficiency (Stape et al., 2004; Le Maire et al., 2013), high productivity (Stape et al., 2010; Binkley et al., 2017), and rapid economic returns (Booth, 2013; Maier et al., 2017; Marcatti et al., 2017; Scolforo et al., 2017). In Brazil the eucalyptus's plantations area is higher than 5.7 million ha (IBÁ, 2017), standing out the Mato Grosso dos Sul State (MS) which had led the expansion over the last five years with an increase of 400 thousand ha and an average growth of 13% per year (IBÁ, 2017; Sena et al., 2017; Scolforo et al., 2018; Reis et al., 2018).

Most of the areas in MS with eucalyptus plantations are within the Savanna biome replaced by degraded pasture and annual crops in the past (Rada, 2013; Lapola et al., 2014; Reis et al., 2018). Savanna is the second largest biome in Brazil (Furley, 1999; IBGE, 2004), composed of forest, savanna and grasslands formations, standing out for its high diversity of plant species (Eiten, 1972; Colodette et al., 2014). Eucalyptus plantations can

support greater diversity of native species than the pasture, and can help or even restore the biodiversity of savanna biome (Hirakuri & Saraiva, 2014).

Given the ecological importance of the savanna and the current growth in eucalyptus plantations in these areas, more studies are needed to quantify how and to which extent land-cover change and land-use practices alter the balance of carbon, water and energy exchange at both ecosystems (da Rocha & Vourlitis, 2011). Changes in land use alter the radiation balance, the ratio between sensible heat flux and latent heat flux, canopy structure, and assimilation rates of carbon and amount of water evaporated (Baldocchi et al., 2001).

The aim of this research initiative was to quantify the carbon, water and energy fluxes in the Brazilian Tropics areas using the eddy covariance technique, meteorological variables, soil and plant measurements in two different studies: in the first study (1), it was reported a full rotation cycle of carbon, water and energy fluxes from a clonal *Eucalyptus grandis* plantation in the MS in Brazil. In this study, it was explore the environmental dependence of intrinsic water- and radiation efficiencies of this plantation to understand the main limitations to its growth from planting to harvest. In the second study (2) was compare the differences in carbon, water and energy fluxes between a native Savanna biome (SAV) and eucalyptus plantations (EUC) from December 2012 to August 2013.

The goals were to (i) determine the fluxes partitioning: net ecosystem exchange (NEE), gross primary production (GPP), and ecosystem respiration (Reco), (ii) to quantify the net ecosystem production (NEP) for each year and for role rotation cycle, (iii) to identify the wind friction velocity (u^*) threshold and uncertainty (u), and (iv) to quantify the seasonal patterns of evapotranspiration (ET), water use efficiency (WUE), canopy conductance (g_c), and intrinsic water-use efficiency (WUE_i) during the study period.

2. LITERATURE REVIEW

2.1. Eucalyptus plantation and Brazilian savanna

Planted forests, mainly Pine and Eucalyptus, play an important role in demand for woody supply, wherein reduce the pressure of natural forests (Cook et al., 2016; FAO, 2016). *Eucalyptus* spp. plantation area reached over 20 million ha in the world, as one of the most extensively cultivated forests mainly planted in tropical and subtropical areas (Wei & Xu, 2003; Booth, 2013; Cook et al., 2016; Liu et al., 2017). This rapid growth in planted area and productivity is due to intense researches, silviculture management, nutrient management, and propagation technique (Stape et al., 2010; Booth, 2013; Rubilar et al., 2018).

Eucalypt plantations are broadly cultivated in many countries across the world, highlighted for Brazil (IBÁ, 2017; Scolforo et al., 2017), China (Zhang et al., 2016; Liu et al., 2017), and India (Ramanagouda et al., 2010; Silva et al., 2017), respectively. Brazilian eucalypt forests stands out for the highest productivity and the shortest rotation of stand in the world (worldwide), which led the forest productivity with average of $35.7 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ in 2016 (IBÁ, 2017). In tropical regions, commercial eucalypt plantations are usually harvested between 5 and 7 years after the planting (Christina et al., 2015). The favorable climate and soil conditions, coupled with continuous investments by Brazilian companies contribute to improvement in forest management (Booth, 2013; Campoe et al., 2016).

Currently, the most product of eucalypt trees planted in Brazil is destined to pulp and paper industry (IBÁ, 2017). In 2016, Brazilian pulp production was 18.8 million tons, reaching the second position of pulp producers worldwide, behind only for USA (IBÁ, 2017). The main destinations for products from Brazilian plated tree industry are China (26%, pulp), Europe (25%, pulp), USA (18%, pulp, paper and panels), Latin America (16%, paper), and others countries (15%).

In 2016, the area with eucalyptus plantations in Brazil was higher than 5.7 million ha (IBÁ, 2017), and they were mainly located in the states of Minas

Gerais (24%), São Paulo (17%) and Mato Grosso do Sul (15%). The Mato Grosso do Sul State (MS) stands out for presenting an increase of 400 thousand ha of forest plantation over the last five years (Figure 1). Therefore, was observed a decrease in planted area in Minas Gerais (MS) and São Paulo (SP) states (Figure 1). This significant increase in planted area with eucalypt forest in the new frontiers (MS) is due to the establish of two large pulp companies in this state, such as Fibria Celulose S.A. and Eldorado Brasil Celulose S.A. (Hirakuri & Saraiva, 2014).

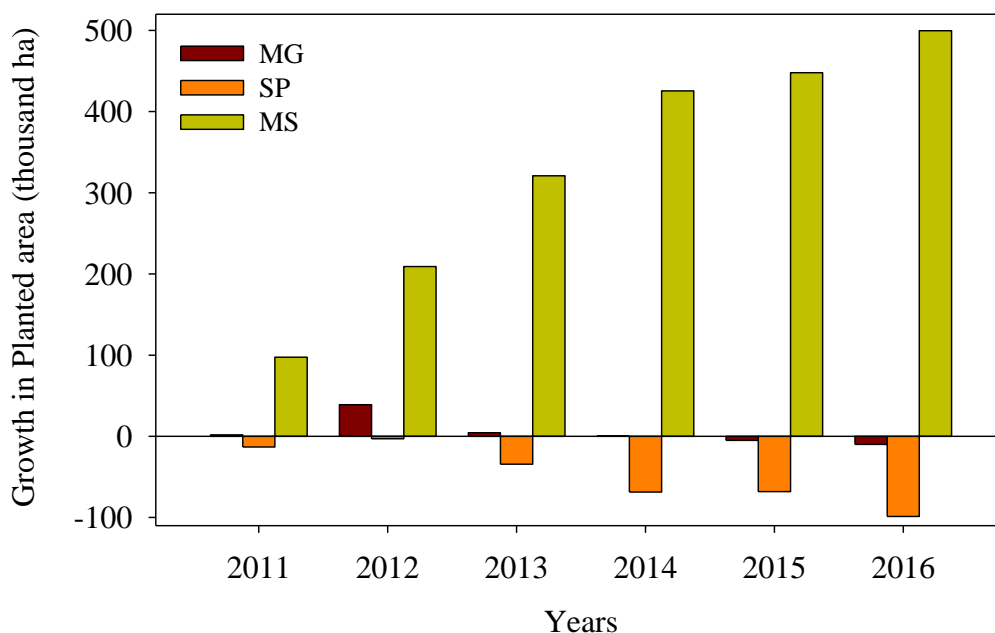


Figure 1. Growth in planted area (thousand ha) regarding 2010 year. Data are from Brazilian tree industry (IBÁ, 2017).

Most of these areas in MS state with eucalyptus plantations are into a Savanna Biome (Furley, 1999; IBGE, 2004) replaced by degraded pasture and annual crops in past (Rada, 2013; Lapola et al., 2014; Scolforo et al., 2018; Reis et al., 2018). The tropical savanna, also known as “Cerrado”, is the second largest biome in Brazil (Figure 2), occupying an area of approximately 23% of the total area of the country (Furley, 1999; Colodette et al., 2014).

This area is composed of forest, savanna and grasslands formations, standing out for its high diversity of plant species (Furley, 1999; Giambelluca et al., 2009) including: the savanna grasslands (*campo limpo*); the savanna with

woody formations less than 2% (campo sujo); the wooded savanna with the tree cover about 2-15% (campo cerrado); the savanna *sensu stricto* with 20-30% of tree cover (cerrado); and woody savanna characterized by semideciduous forest, with a predominance of trees about 15 m high (cerradão).

Given the ecological importance of the savanna and the current growth in eucalyptus plantations in these areas, more studies are needed to quantify how land-cover change and land-use practices alter the balance of carbon, water and energy exchange at both ecosystems (Luyssaert et al., 2007; da Rocha & Vourlitis, 2011). Currently, studies to understanding and characterize the biogeophysical functioning of each of these forest types have been increase in these area (Rody, 2013; Vasconcelos, 2014; Teixeiras, 2017; Reis et al., 2018).

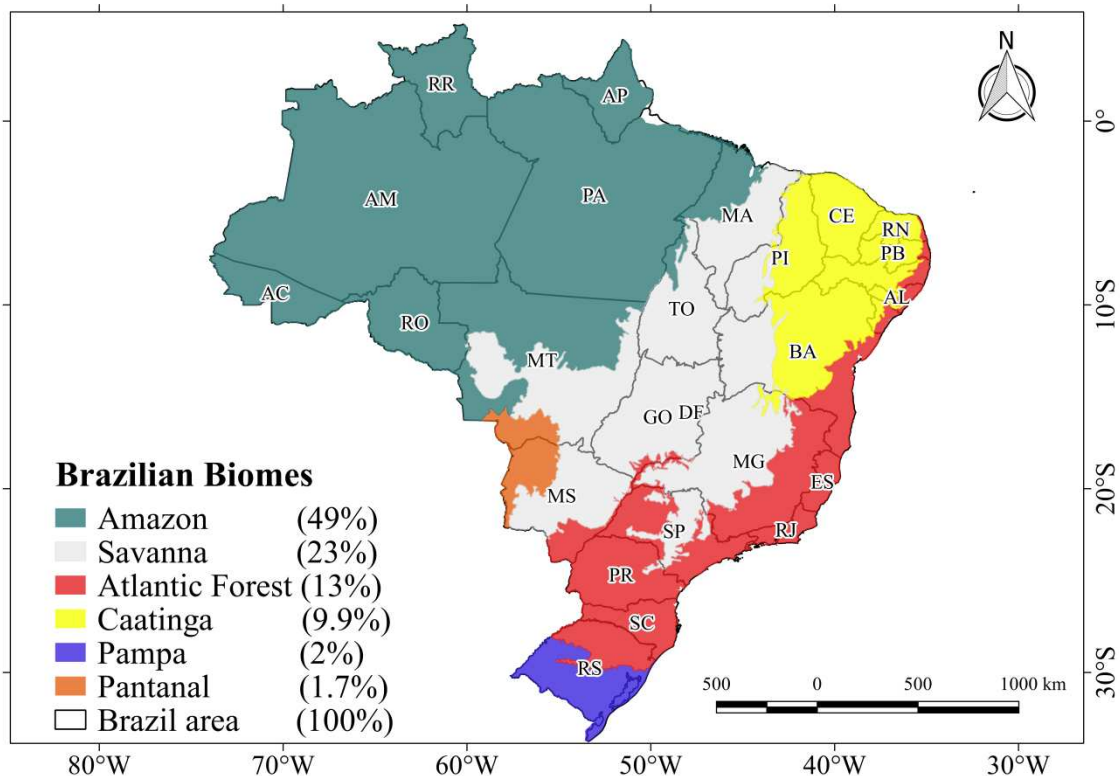


Figure 2. Brazilian biomes and the corresponding percentage of the total area of the country. Total area (km²) corresponding each biome in Brazil (8,514,877): Amazon (4,196,943), Savanna (2,036,448), Atlantic Forest (1,110,182), Caatinga (844,453), Pampa (176,496), and Pantanal (150,355). Data are from Brazilian Institute of Geography and Statistics (IBGE, 2004) and Colodette et al. (2014).

2.2. Eddy Covariance Method

The eddy covariance (EC) method is a micrometeorological technique for quantify carbon, water and energy exchanges between ecosystems and the atmosphere (Moncrieff et al., 1996; Baldocchi et al., 2001; Aubinet et al., 2012). The EC is one of the most accurate and direct method that provides measurements of mass and energy fluxes over multiple timescales (hour, days, seasons, and years) from small to large areas, with minimal disturbance to the ecosystem (Baldocchi et al., 2001; Burba, 2013).

The EC measurements are used as a tool to estimate of CO_2 flux, latent heat flux (LE), and sensible heat flux (H) by ecosystems (Baldocchi et al., 2001). This micrometeorological technique is based on statistical procedures by covariance of the vertical wind velocity (w) with the CO_2 and H_2O concentration and the air temperature (T) (Baldocchi 2003; Aubinet et al., 2012). The transport of these variables in the soil-plant-atmosphere system is carried out by turbulent movements in the atmospheric boundary layer, by eddies (Figure 3).

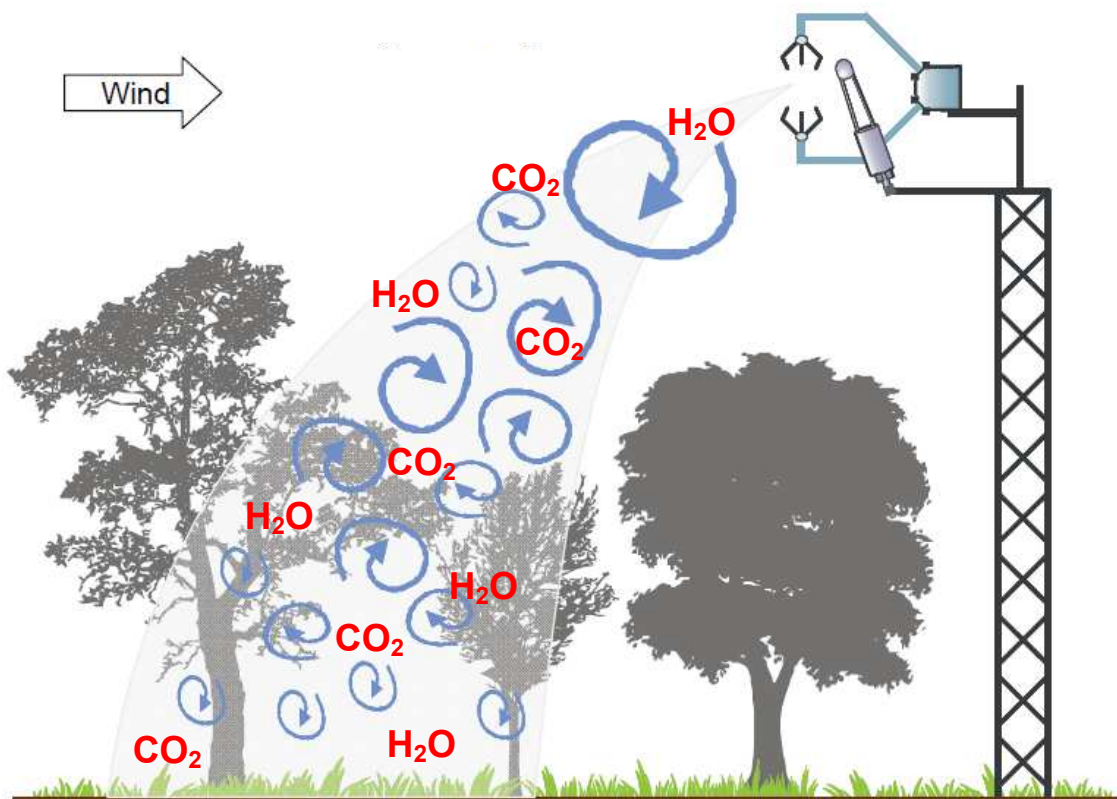


Figure 3. Eddy covariance method used to estimate fluxes exchanged between ecosystems and the atmosphere. Modified from Wolf (2010).

The turbulent fluxes of CO₂ (F_c), latent heat flux (LE), and sensible heat flux (H) are obtained by the following equations (Aubinet et al., 2012; Burba, 2013):

$$F_c = \rho \overline{w' C'} \quad (1)$$

$$LE = \rho \lambda \overline{w' q'} \quad (2)$$

$$H = \rho c_p \overline{w' T'} \quad (3)$$

where F_c is the CO₂ flux ($\mu\text{mol m}^{-2} \text{s}^{-1}$), ρ is the dry air density (kg m^{-3}), w is the vertical wind speed (m), C is the concentration of CO₂ (mg m^{-3}), LE is the latent heat flux (W m^{-2}), λ is the latent heat of vaporization for water (J kg^{-1}), q is the water vapor mixing ratio (kg m^{-3}), H is the sensible heat flux (W m^{-2}), c_p is the specific heat of air ($\text{J kg}^{-1} \text{K}^{-1}$), and T is the air temperature ($^{\circ}\text{C}$).

The EC method requires a correctly site implementation setting up, advanced instrumentation coupled to intense data processing systems (Burba, 2013; Baldocchi et al., 2015). Field experiments with the eddy covariance method requires a 3D-sonic anemometer for wind velocity in three directions and air temperature (T), and an infrared gas analyzer (IRGA) for carbon dioxide (CO₂) and water vapor (H₂O) (Figure 3). Attached with others sensors which possibly help interpreted the flux measurements, such variables: solar radiation, air temperature, air relative humidity, rainfall, soil temperature, soil heat flux, soil moisture, leaf area index, and others variables if necessary (Burba, 2013).

The eddy covariance method is more accuracy generally when atmospheric conditions are steady, the vegetation type is homogeneous and is located on a relatively flat terrain (Baldocchi et al., 2001). Also, the EC instrumentation (3D-sonic and IRGA) must be installed within the turbulent boundary layer (Aubinet et al., 2012), where the fluxes of mass and energy are transported by turbulence process in a timescale of about an hour or less (Stull,

1988). In general, the height of the EC sensors depends on the height of the vegetation, the adequate length of fetch/footprint (fluxes are measured only at area of interest), the range of wind velocity, and the frequency response of the sensors (e.g. 10 or 20 Hz) (Baldocchi et al., 2001).

The fluxes measurements with eddy covariance method are not perfect, which requires appropriate maintenance and calibration of sensors and data acquisition equipment (Lee et al., 2004). Also, the EC technique is associated with random or biased errors (Moncrieff et al., 1996; Baldocchi et al., 2001). Briefly, these errors are associated with: system time response; tube attenuation (for close path analyzer); path and volume averaging; sensor separation (between anemometer and gas analyzer); sensor response mismatch; low-pass filtering; high-pass filtering; digital sampling; spikes and noise (due to high frequency of instantaneous data); unlevelled anemometer; wind angle of attack; sensors time delay; sonic heat flux errors; density fluctuations (Burba, 2013).

Many corrections can be applied to minimize or avoid these errors during the raw data processing, including: spike removal; turbulence fluctuations; coordinate rotation; angle-of-attack correction; time delay adjustment; frequency response corrections; sonic heat flux correction; WPL density terms; instrument specific correction (Lee et al., 2004; Burba, 2013). Spectral and co-spectra analysis and quality control are used to validation of all these corrections after processed data (Burba, 2013). Summarize, the entire process of experimental instrumentation, implementation and data processing are specified at each site (Aubinet et al., 2012).

All of these corrections are done by software package or self-written computer programs using Fortran or Matlab. Currently, the most software to processing raw eddy covariance data are: EddyPro 6.2 (LI-COR Bioscience); EdiRe (University of Edinburgh, UK); ECpack (Wageningen University, the Netherlands); TK3 (University of Bayreuth, Germany); Alteddy (Wageningen University, the Netherlands); EddySoft (Max Planck Institute for Biogeochemistry, Germany); and EddyUH (University of Helsinki, Finland).

3. MATERIALS AND METHODS

3.1. Site Description

The experimental site consisted of *Eucalyptus* plantations (clonal *Eucalyptus grandis*) and Savanna biome located at Midwest of Brazil, Mato Grosso do Sul State (21°04'S-52°21'W, 387 m above sea level), in forested areas belonging to the Fibria Celulose S.A. (Figure 4). According to the Köppen climate classification system, the climate in this area is Aw (tropical with dry winter) characterized by well-defined wet (October to April) and dry (May to September) seasons, with mean annual air temperature ranging from 22 to 24 °C and total annual rainfall 1300 to 1600 mm (Alvares et al., 2013). The soil is classified as a rhodic, clay-loam Oxisol (US Soil Taxonomy), with gentle slopes less than 2%.



Figure 4. Location of study site with eucalyptus plantations and Savanna biome in Brazilian Tropics.

First study: Carbon balance and evapotranspiration of Eucalyptus plantations in Brazil during a rotation cycle

For the first study, were analyzed 9 years of eddy covariance CO₂ and H₂O exchange data from a commercial eucalypt plantation, spanning one full rotation cycle (including 8 years of growth, harvest of trees, and 1 year with site preparation and planting of new trees; Table 1). *Eucalyptus* trees were planted in November 2007 at a 3.6 x 2.5 m spacing (1111 trees per hectare) covering an area of 144.4 ha using standard forestry practices in commercial *Eucalyptus* plantation. The fetch and footprint were assumed adequate for measurements encompassing the interest area (1/100) (Baldocchi, 2003).

Second study: Seasonal variability of carbon, water and energy fluxes in Eucalyptus plantations and savanna forest in Brazilian Tropics

For the second study, were compared carbon, water and energy fluxes in two different ecosystems: in a native Savanna forest and in a commercial eucalypt plantation (clonal *Eucalyptus grandis*), separated by 5 km apart (Figure 4; Table 2). The native Savanna biome is in a primary forest occupying an area of about 1570 ha, characterized by semi deciduous forest, with a predominance of trees about 10 m high (Furley, 1999; Giambelluca et al., 2009; da Rocha & Vourlitis, 2011). The area chosen for installation of the tower were made by a prior flora survey (Reis et al., 2018). The tower was allocated among the most predominant and representative trees species in the region as *Cupania vernalis* Camb., *Dipterix alata* Vog., *Hymenea stigonocarpa* Mart. ex Hayne, and *Tapirira guianenses* Aubl., with 9.4, 11.9, 12.5 and 9.2 meters height, respectively. *Eucalyptus* trees (62 to 70 months) were planted at a 3.6 x 2.5 m spacing (1111 trees per hectare) covering an area of 81.1 ha using standard forestry practices in commercial *Eucalyptus* plantation (Christina et al., 2015).

Table 1. Site information of canopy and tower height over 9 years of rotation cycle in eucalyptus plantations located in Brazilian Tropics.

Age	Months	Canopy height (m)	Tower height (m)
1	Nov-Feb	0.50	4.16
	Mar-Jun	0.50	4.16
	Jul-Oct	3.20	5.92
2	Nov-Feb	3.20	5.92
	Mar-Jun	5.00	9.64
	Jul-Oct	5.00	9.64
3	Nov-Feb	9.00	15.22
	Mar-Jun	14.30	18.94
	Jul-Oct	17.30	20.80
4	Nov-Feb	20.50	24.52
	Mar-Jun	20.50	24.52
	Jul-Oct	23.00	26.38
5	Nov-Feb	23.00	26.38
	Mar-Jun	25.00	29.50
	Jul-Oct	25.00	29.50
6	Nov-Feb	25.00	29.50
	Mar-Jun	25.00	29.50
	Jul-Oct	28.00	36.00
7	Nov-Feb	28.00	36.00
	Mar-Jun	28.00	36.00
	Jul-Oct	28.00	36.00
8	Nov-Feb	28.00	36.00
	Mar-Jun	28.00	36.00
	Jul-Oct	28.00	36.00
1	Nov-Feb	0.50	4.16
	Mar-Jun	0.50	4.16
	Jul-Oct	3.20	5.92

Table 2. Localization of the micrometeorological tower and canopy height in both Eucalyptus and Savanna ecosystem in Brazilian Tropics.

Ecosystems	Canopy Height (m)	Tower Height (m)	Latitude (S)	Longitude (W)	Elevation m (a.s.l)
Eucalyptus plantations	28	36	21°00'14"	52°21'53"	387
Savanna	12	20	21°03'11"	52°23'20"	391

3.2. Eddy Covariance Measurements

The eddy covariance (EC) system was positioned above the canopy tree on top of micrometeorological tower (Figure 5). The turbulent fluxes of CO₂ and H₂O between the forest canopy and the atmosphere were measured with an open-path infrared gas analyzer (LI-7500, LICOR Inc., Lincoln, Nebraska, USA) and a 3-dimensional sonic anemometer (CSAT3, Campbell Scientific, Logan, Utha, USA). A datalogger (CR1000, Campbell Scientific Instruments, Utah, USA) was used to record raw data at 20 Hz (20 data per second) of measurements (Figure 6).



Figure 5. Micrometeorology tower at eucalyptus plantations (36 m, a) and Savanna biome (20 m, b) of experimental site in Brazilian Tropics.

Micrometeorological variables were measured above canopy: global/shortwave radiation (CMP3, Kipp & Zonen B.V., Delft, Netherlands), air temperature and relative humidity (HMP45C, Vaisala Inc., Vantaa, Helsinki, Finland), photosynthetically active radiation (PQS 1, Kipp & Zonen B.V., Delft, Netherlands), net radiation (NR Lite 2, Kipp & Zonen B.V., Delft, Netherlands), and rainfall (TB3-CS700-L, Hydrological Services Pty. Ltd., Sydney, Australia). At ground level was measured soil water content (EnvirosMart, Sentek Pty Ltd., Stepney, Australia) placed at 10, 20, 40, 60, 100, 140, 180 cm of depths, and soil heat flux was buried 8 cm below the surface (HFP01, Hukseflux Thermal Sensors B.V., Delft, Netherlands). Data were collected continuously at 5 sec intervals with 30 min averages or totals were recorded using a datalogger (CR1000, Campbell Scientific Instruments, Utah, USA).

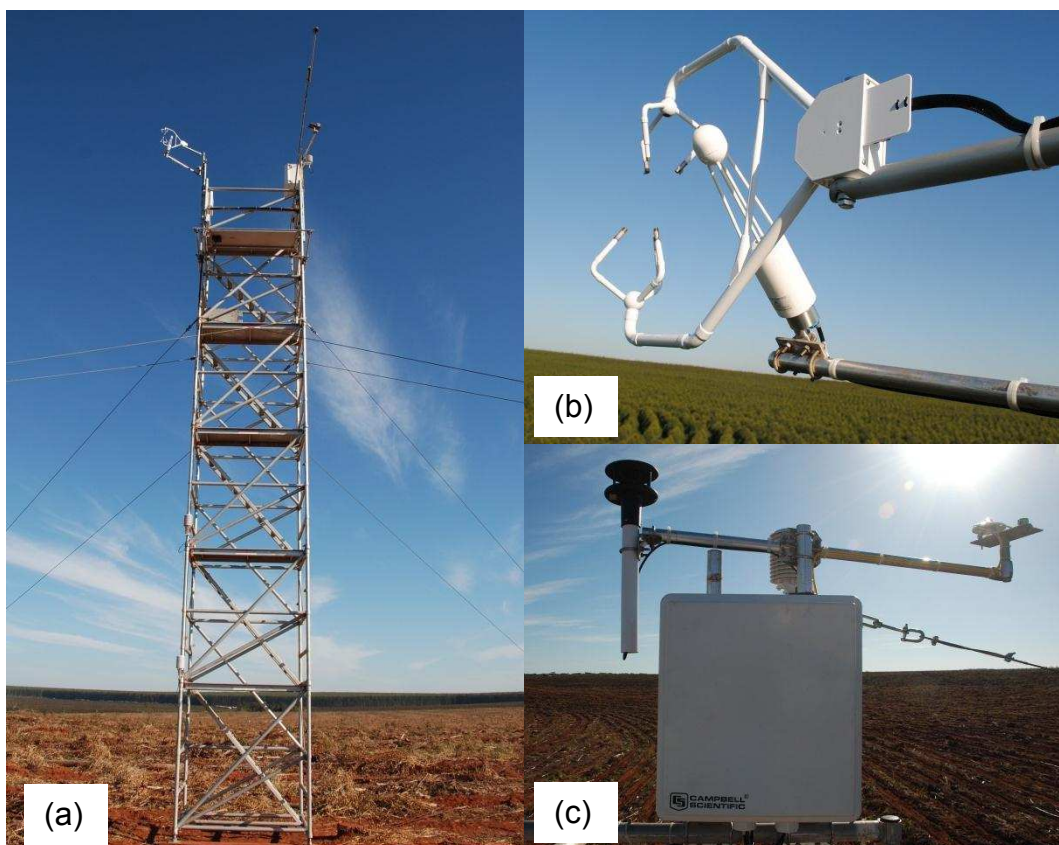


Figure 6. Micrometeorological tower (a), eddy covariance system (b) and meteorological sensors (c) installed at experimental site in eucalyptus plantations in Brazilian Tropics.

3.3. Data Processing, correction and u^* threshold estimates

The covariance between vertical wind speed and concentration of CO_2 , H_2O and air temperature were calculation from the 20 Hz fluctuations around 30-minute averaging periods, using the EddyPro 6.2 software (LI-COR Biosciences, Lincoln, NE, USA). Despiking and raw data statistical screening (Vickers & Mahrt, 1997) were included in the preliminary processing and the outliers were discarded. Block averages were used to extract the turbulence fluctuations from times series data (Gash & Culf, 1996). The compensate density fluctuations (Webb et al., 1980) and sonic temperature (Schotanus et al., 1983) were corrected. The mean vertical wind speed (w) was forced to be zero by a double coordinate rotation (Kaimal & Finnigan, 1994). Low frequency spectral corrections were applied according to the analytic method described in Moncrieff et al. (2004). High frequency spectral correction was based on fully analytic method of Moncrieff et al. (1997).

Afterward the process of the mean 30-min fluctuations covariances, the CO_2 (NEE) and water (LE) fluxes were filtered by quality control (0 – highest quality data; 1 – good quality data, keep for integrations or discard for empirical relationships; 2 – questionable data quality, remove form the data) procedures (Mauder & Foken, 2004), wherein data with a flag > 1 were discarded. Spike fluxes were flagged during rainfall periods due to wet sensor conditions. Remaining outliers in the times series of the half hourly flux values were removed using a transfer function lead-lag filter block implement in Matlab software (R2015a, MathWorks, Natick, MA, USA), with the following conditions: rain period, wind velocity $< 0.5 \text{ m s}^{-1}$, and photosynthetically active radiation $< 200 \mu\text{mol m}^{-2} \text{ s}^{-1}$.

During the periods with low turbulence conditions, indicated by low friction velocity (u^*), the data fluxes must be filtered to avoid bias and uncertainties (Papale et al., 2006). The u^* threshold was specifically derived for each year according to Reichstein et al. (2005). Annual u^* thresholds ranged from 0.20 to 0.41 m s^{-1} , with mean of 0.28 ± 0.08 for eucalyptus ecosystem, and the u^* threshold was 0.37 m s^{-1} for savanna ecosystem.

3.4. Gap-filling and flux partitioning

The data was gap filled considering the covariation of fluxes with meteorological variables and the temporal autocorrelation of fluxes (Reichstein et al., 2005), using a look up table and the mean diurnal course algorithms described by Falge et al. (2001). Fluxes of net ecosystem exchange (NEE, $\mu\text{mol m}^{-2} \text{s}^{-1}$) between carbon uptake and release by ecosystems were partitioned into gross primary production (GPP, $\mu\text{mol m}^{-2} \text{s}^{-1}$) and ecosystem respiration (R_{eco} , $\mu\text{mol m}^{-2} \text{s}^{-1}$), respectively:

$$NEE = GPP + R_{\text{eco}} \quad (4)$$

Flux partitioning was computed based to night-time method (Reichstein et al., 2005) wherein use the exponential regression model by Lloyd & Taylor (1994) from seasonal data to estimate the ecosystem respiration:

$$R_{\text{eco}} = R_{\text{eco.ref}} e^{E_0 \left(\frac{1}{T_{\text{ref}} - T_0} - \frac{1}{T - T_0} \right)} \quad (5)$$

where R_{eco} is ecosystem respiration ($\mu\text{mol m}^{-2} \text{s}^{-1}$), $R_{\text{eco.ref}}$ is ecosystem base respiration at 15 °C, E_0 is an activation energy parameter, T_{ref} is reference temperature is set to 15 °C, T is air temperature, and T_0 is an parameter set to -46.02 °C.

Gap-filling technique and flux partitioning were carried according to Reichstein et al. (Reichstein et al., 2005) using the online eddy covariance gap-filling tool (REddyProc - <http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/>). The annual NEE uncertainty (u , $\mu\text{mol m}^{-2} \text{s}^{-1}$) associated with gap-filling approach was estimated according to Aurela et al. (Aurela et al., 2002) and Noormets et al. (2010):

$$u = \sqrt{\frac{\sum_{i=1}^n (NEE_{obs} - NEE_{mod})^2}{(n-1).n}} \quad (6)$$

where n is the number of observations, NEE_{obs} is NEE measurements values, and NEE_{mod} is NEE modeled values.

3.5. Eddy Covariance flowchart

The following steps show the pre-processing of raw data, processing, and post-processing data including: quality control, gap-filling of missing data and fluxes partitioning used in this research.

In this research, the file with ~15 days of raw data from eddy covariance system was split to 30 minutes files into TOB1 format (Table Oriented Binary Format 1) using the LoggerNet software by Campbell Scientific. Also, environmental variables were used in EC data processing, such as: ambient temperature, ambient pressure, ambient relative humidity, global radiation, longwave incoming radiation, and photosynthetically active radiation. Note: the EddyPro 6.2 software support any environmental variable, but only these previous six variables will do part of the mathematical calculus (see EddyPro® Software Instruction Manual).

In this research, it was used the EddyPro 6.2 software program (<https://www.licor.com/env/support/product?p=eddypro>) to process the raw eddy covariance data. The all data format embedded into to EddyPro software are available in (EddyPro® Software Instruction Manual). After the raw data processed, was used the Matlab software (R2015a, MathWorks, Natick, MA, USA) to post-processed data, including: quality control, rain filter and spikes removal.

The gaps due to these post-processing filters and others problems in EC system was filled according to Falge et al. (Falge et al., 2001). The gap-filling method is needed to reconstruct the missing periods and to calculate sums to estimate annual balance. The principal gap-filling methods are: mean diurnal variation (MDV), Look-up tables (LUT), Artificial Neural Networks (ANNs),

Nonlinear Regressions (NR), and process models (Falge et al., 2001; Aubinet et al., 2012).

In this research, it was used the online eddy covariance gap-filling tool (REddyProc - <http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/>) to filled half-hourly meteorological and micrometeorological variables (Figure 7), such as: air temperature (T_{air} , °C), relative humidity (RH, %), solar radiation (R_g , $W\ m^{-2}$), net ecosystem exchange (NEE, $\mu mol\ m^{-2}\ s^{-1}$), latent heat flux (LE, $W\ m^{-2}$), sensible heat flux (H, $W\ m^{-2}$) and friction velocity (u^* , $m\ s^{-1}$). The u^* was used to filtering removes mainly nighttime data due to stable conditions of the turbulence in the atmosphere. The u^* threshold need to identify for each specific site, often specific year and must be estimated starting from the data (Papale et al., 2006).

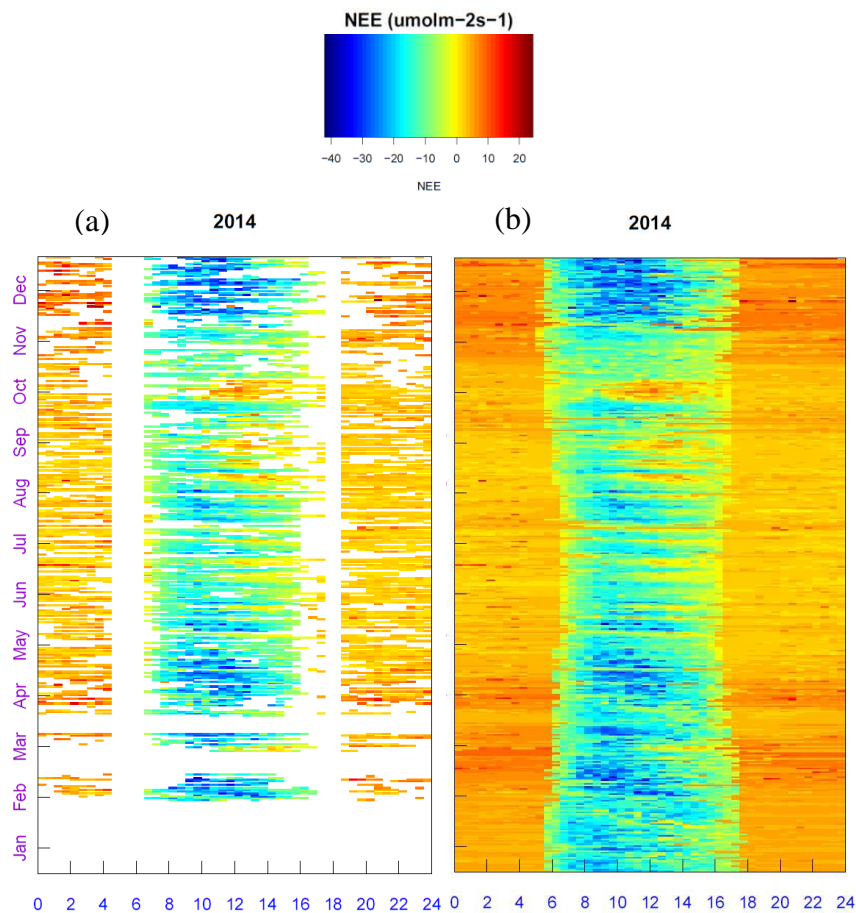


Figure 7. Fingerprint of net ecosystem exchange (NEE, $\mu mol\ m^{-2}\ s^{-1}$) before gap-filling (a) and after NEE filled (b) from Brazilian ecosystem. Positive values of NEE - represent a release of CO_2 from the ecosystem into the atmosphere, and negative values of NEE - denote uptake of CO_2 by the ecosystem.

To describe the processes responsible for carbon flux, the net ecosystem exchange (NEE) was partitioning into the gross primary production (GPP) and ecosystem respiration (Reco) (Aubinet et al., 2012; Baldocchi et al. 2018). Many flux partitioning algorithms have been used for scientist, the two principal are nighttime data based methods (Reichstein et al., 2005a) and daytime data based methods (Lasslop et al., 2010). The schematic eddy covariance flowchart for data processing, gap-filling, and fluxes partitioning used in this research are show in Figure 8.

All carbon fluxes (NEE, GPP and Reco) were integrated in daily, monthly and annual sums, according to the following convert units (considering: 30 minutes = 1800 seconds; 1 μ = 10^{-6} ; 1 mol CO₂ = 12 g Carbon; 1 ha = 10000 m²):

$$\frac{\mu\text{molCO}_2}{\text{m}^2\text{s}} \rightarrow \frac{10^{-6} * 12\text{gC}}{\text{m}^2} * 1800 \rightarrow \frac{\text{gC}}{\text{m}^2} * 0.0216 \quad (7)$$

$$\frac{\text{gC}}{\text{m}^2\text{year}} \rightarrow 10^{-6} * \frac{\text{tC}}{\frac{1}{10000}\text{ha.year}} \rightarrow 10^{-2} * \frac{\text{tC}}{\text{ha.year}} \quad (8)$$

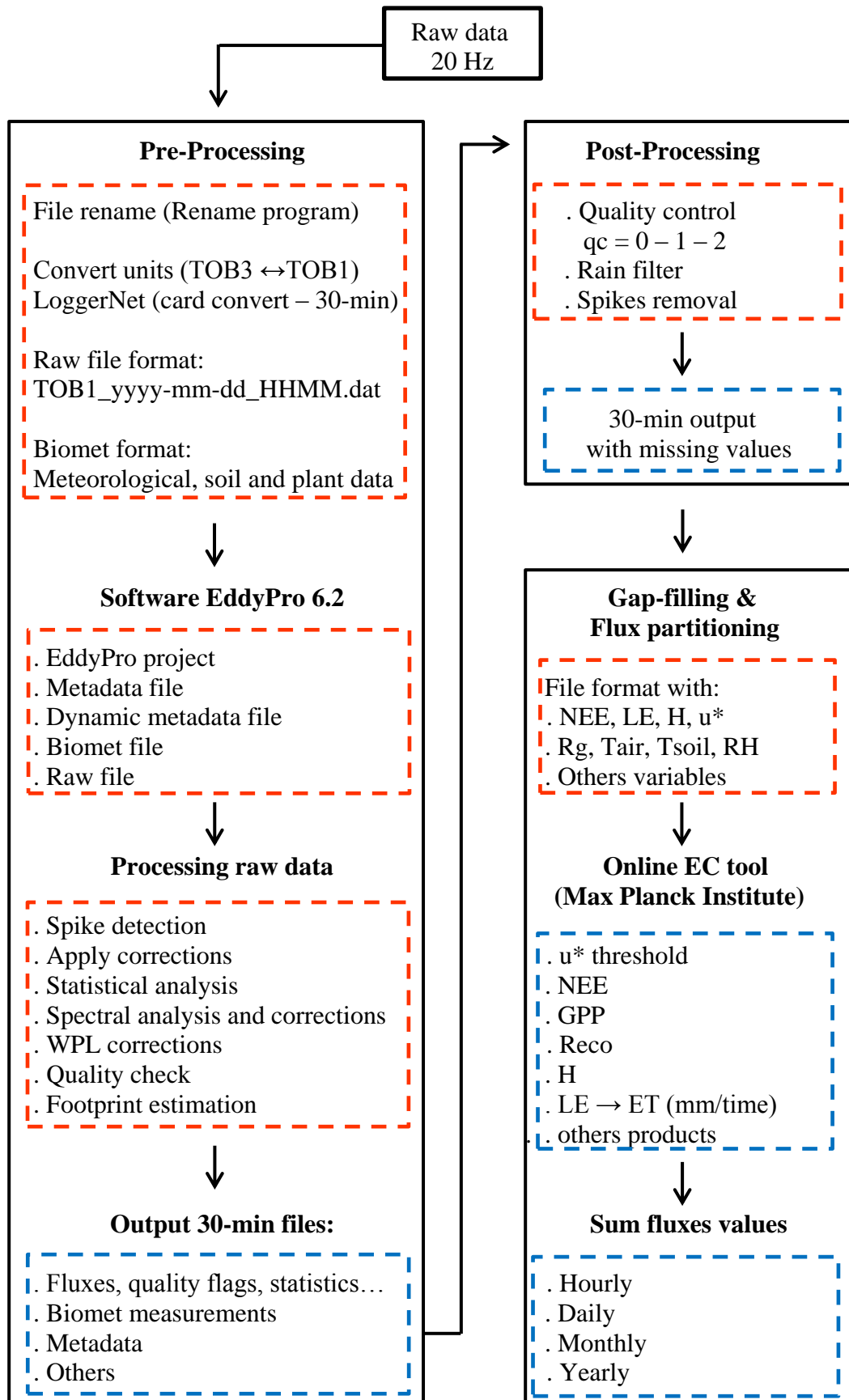


Figure 8. Eddy covariance flowchart for data processing, gap-filling, and fluxes partitioning. Note: red boxes (input files) and blue boxes (output files).

3.6. ET, WUE, WUE_i and g_c

The total ecosystem evapotranspiration (ET, mm 30-min⁻¹) including forest transpiration and evaporation from soil and canopy interception was converted from latent heat flux (LE, W m⁻²), by the formula (Aubinet et al., 2012):

$$ET = 1800 \frac{LE}{10^3(3147.5 - 2.37T_{air})} \quad (9)$$

where ET is evapotranspiration (mm 30-min⁻¹), LE is latent heat flux (W m⁻²), 1800 is conversion factor (1800 seconds), 10³ (3147.5 – 2.37T_{air}) is λ, latent heat of vaporization of water (J kg⁻¹), and T_{air} is air temperature (K).

Water-use efficiency (WUE, g C kg⁻¹ H₂O⁻¹) was calculated by the ratio of gross primary production (GPP) and evapotranspiration (ET). Intrinsic water-use efficiency (WUE_i, g C kg⁻¹ H₂O⁻¹) was calculated by the ratio of gross primary production (GPP) and canopy conductance (g_c).

Canopy conductance (g_c, m s⁻¹) was calculated by inverting the Penman-Monteith equation (Monteith, 1965). It can be expressed in its simplest form as follows (Noormets et al., 2010):

$$g_c = \frac{PETR_w}{\rho VPDR_d} \quad (10)$$

where P is atmospheric pressure (kPa), ET is evapotranspiration (kg m⁻² s⁻¹), R_w is universal gas constant specific for water vapor (461.495 J kg⁻¹ K⁻¹), ρ is air density (kg m⁻³), VPD is vapor pressure deficit (kPa), and R_d is universal gas constant specific for dry air (287.058 J kg⁻¹ K⁻¹).

3.7. Energy balance approach

The energy balance closure (EBC) is the relationship between the available energy ($R_n - G$) and the sum of turbulent fluxes ($H + LE$), is commonly used to validate the eddy covariance measurements (Wilson et al., 2002; Culf et al., 2004; Foken, 2008; Leuning et al., 2012; Reed et al., 2017). Energy balance was applied to assess the accuracy of eddy covariance measurements following the simplified equation:

$$R_n = H + LE + G \quad (11)$$

where R_n is net radiation, H is sensible heat, LE is latent heat, and G is soil heat flux (all terms expressed in $W\ m^{-2}$). It was neglect energy storage and energy used by photosynthesis. All data was filtered according to quality control ($qc = 0$), rain periods and data points with $LE > 1300\ W\ m^{-2}$ or $LE < -200\ W\ m^{-2}$ and $H > 1000\ W\ m^{-2}$ or $H < -200\ W\ m^{-2}$, but not gap-filled 30-min R_n , H , LE , and G .

3.8. Leaf area index

Leaf area index (LAI) was obtained using the canopy analyzer (LAI 2000 LICOR Inc., Lincoln, Nebraska, USA). The LAI 2000 was used in remote mode, with two optical sensors, a fixed control unit of the equipment was installed in open areas and an unit handset measurements below the canopy (Welles & Norman, 1991; Ryu et al., 2010). Four plots (30 x 30 m) were designated within a radius of 300 m around the tower. In each plot, 25 readings were made under the canopy with the LAI 2000, every two months during the study period. Also the LAI was obtained from images using Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) from MODIS sensor (NASA) according to (Rody, 2013).

4. RESULTS AND DISCUSSION

4.1. First study: *Eucalyptus* plantations over 9 years in Brazil

The first study aimed to analyze 9 years of eddy covariance CO₂, H₂O and energy exchange data from a commercial eucalypt plantation, spanning one full rotation cycle, including 8 years of growth, harvest of trees, and 1 year with site preparation and planting of new tree.

4.1.1. Microclimate and carbon fluxes

Daily microclimate and carbon fluxes time series during the spanning one full rotation cycle of eucalypt plantation are shown in Figure 9. During 9-year study period, the carbon fluxes and environmental variables followed the seasonal drought and wet conditions, and also including site preparation and planting of new trees. Differences in carbon fluxes due to variability in meteorological conditions and forest management were observed in other eucalypt plantations (Pereira et al., 2007; Cabral et al., 2011; Rodrigues et al., 2011).

Seasonal daily patterns in air temperature (T_{air}), photosynthetic active radiation (PAR), vapor pressure deficit (VPD) varied clearly across 9-year study period (Figure 9b and c), reached peak in summer season (December to March) and decline in winter season (June to September). T_{air} ranged between 7.8 to 32.9 °C, with an average of 23.9 °C ± 3.3. The daily pattern of T_{air} was well correlated with PAR at all years (Figure 9b). Average diurnal PAR was 37.3 mol m⁻² day⁻¹ ± 12, with a minimum of 0.8 mol m⁻² day⁻¹ and a maximum of 69.5 mol m⁻² day⁻¹. The vapor pressure deficit (VPD) followed the period of drought conditions, with a maximum value of 4.07 kPa ± 0.65 (Figure 9c). SWC varied with seasons and was highest during wet period, with a daily maximum of 1.23%, and decreased in dry period, with a daily minimum of 0.54%, with an average of 0.78% ± 0.17 (Figure 9d). Total annual rainfall ranged between 986.3 to 1496.8 mm, with an annual average of 1238.1 mm (Figure 9d). In general, the high rainfall (74 to 115 mm day⁻¹) was observed during summer season.

Across all years, carbon fluxes consistently peak in summer season (December to March), and decline in winter season (June to September), wherein represented the wet (rainfall mean of 646 mm) and dry (rainfall mean of 243 mm) period in this region (Figure 9a and d). The daily net ecosystem exchange (NEE) ranged between 8.8 to $-9.9 \text{ g C m}^{-2} \text{ day}^{-1}$, with average of -2.5 ± 3.0 (mean \pm SD), negative NEE denotes the net carbon uptake of the ecosystem. Positive NEE was observed in the first year between November to April when the ecosystem respiration (Reco) was higher than photosynthesis (GPP) noticed by Cabral et al. (2011) in the first year of eucalyptus plantation, and also reported by Rodrigues et al. (2011) after the harvest of trees the values of NEE became positive. Daily gross primary production (GPP) ranged between -4.1 to $19.9 \text{ g C m}^{-2} \text{ day}^{-1}$, with average of 8.2 ± 4.0 . The daily ecosystem respiration (Reco) ranged between 0.8 to $13.7 \text{ g C m}^{-2} \text{ day}^{-1}$, with average of 5.6 ± 2.5 . Similar to NEE, was observed an increased in GPP (1.9 to $13.9 \text{ g C m}^{-2} \text{ day}^{-1}$, 86%) and Reco (2.8 to $8.9 \text{ g C m}^{-2} \text{ day}^{-1}$, 68%) fluxes in the first year of planting, due to the fast growth of trees (Figure 9a).

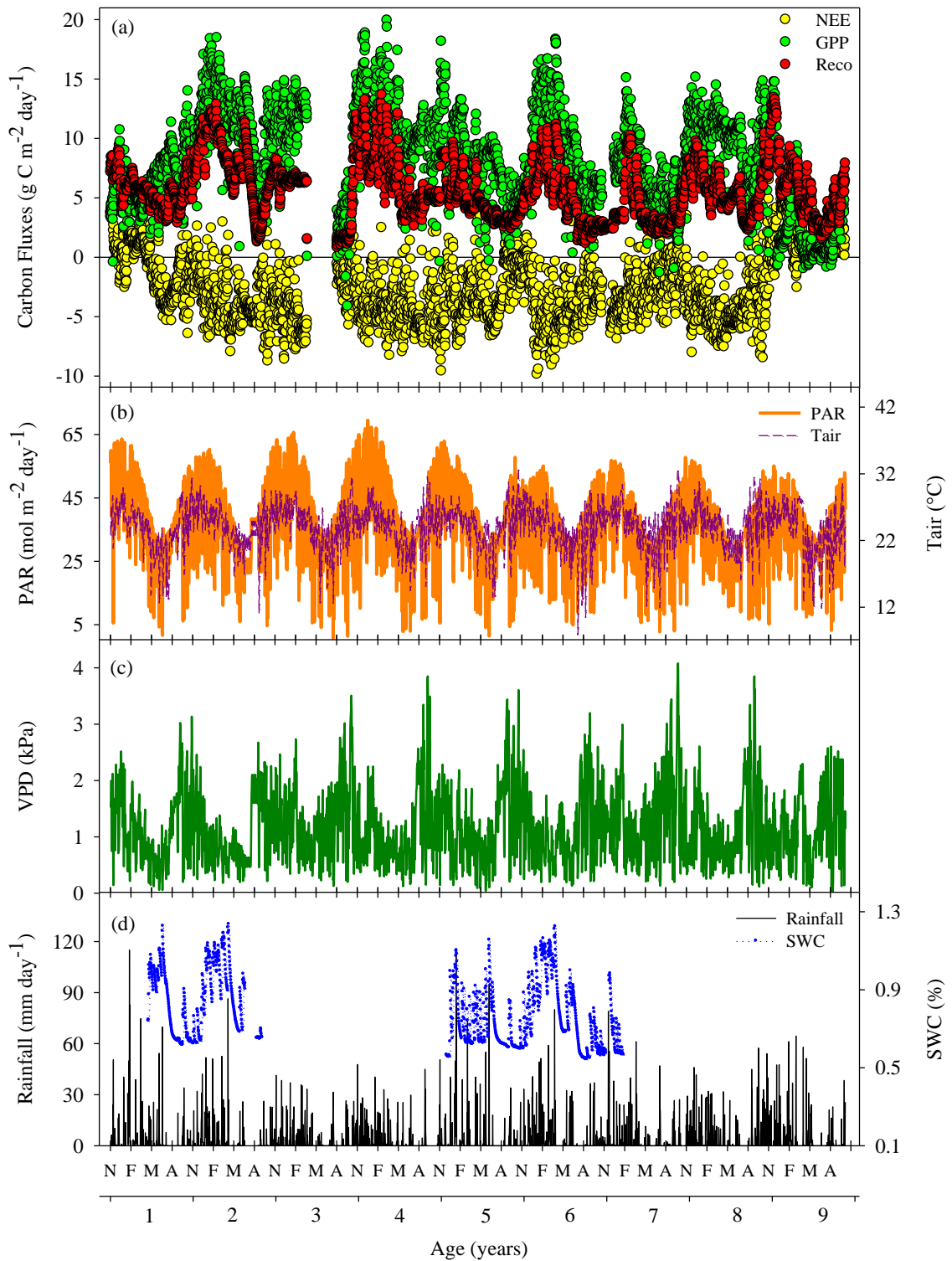


Figure 9. Daily carbon fluxes (net ecosystem exchange (NEE), gross primary production (GPP), and ecosystem respiration (Reco)). Daily cumulative photosynthetically active radiation (PAR) and rainfall. Mean daily values of air temperature (Tair), water vapor saturation pressure deficit (VPD), and soil water content (SWC) during 9 years at an eucalyptus plantation in Brazilian tropics.

4.1.2. NEE annual and seasonal patterns

From 1 to 9 years total cumulative NEE, GPP and Reco are shown in Figure 10. Based on the cumulative annual NEE data, the eucalyptus plantations were a strong carbon sink during 1 to 8 years, but it became a weak carbon source after harvest of trees (Figure 10a). Before the harvest of trees (1 to 8 years), the annual NEE sum increased from -256 to -1515 g C m⁻² yr⁻¹, the annual GPP sum increased from 2312 to 4059 g C m⁻² yr⁻¹, and the annual Reco sum increased from 1195 to 2751 g C m⁻² yr⁻¹ (Table A2). These results compare well with the findings in *Eucalyptus* plantations (Pereira et al., 2007; Cabral et al., 2011; Rodrigues et al., 2011) and in *Eucalyptus* forest (Keith et al., 2012; van Gorsel et al., 2013; Griebel et al., 2016; Hinko-Najera et al., 2017) (Table 3).

Thus, the carbon balance during a complete rotation cycle of eucalypt plantation was strongly a net flux of CO₂ from the atmosphere to the ecosystem, with a total carbon sequestration of 87 t C ha⁻¹ (Table A1). After harvest of trees (9 year, including site preparation and planting of new trees), the annual NEE, GPP, and Reco sum were 883, 1248, 2132 g C m⁻² yr⁻¹ respectively, indicating a weak carbon source for this year (Figure 10, Table A1). Therefore, the carbon balance over 9 years analyzed in eucalyptus plantations was 78 t C ha⁻¹. The annual NEE uncertainty over 9-years ranged between ± 10 to ± 66 g C m⁻² yr⁻¹, based on the differences between observations and calculated fluxes (Table A1).

The seasonal and interannual differences in NEE were reflected in the GPP and Reco totals among years (Figure 10, Table A1). Annual sum of GPP (variation of ~70%) presented higher variability compared to Reco (variation of ~51%) wherein was more consistent (Figure 10a and b). The GPP/Reco ratio varying between 1.12 and 1.76 during 1 to 8 years, and the ratio dropped to 0.59 in 9-year (Table A1). These values are consistent than those reported by others eucalypt studies, with 1.28 to 1.40 by Cabral et al. (2011) and 1.43 to 2.13 by Rodrigues et al. (2011). Indeed, the seasonal variability in GPP and Reco was followed the leaf area index (LAI), wherein varied by 0.14 m² m⁻² in the beginning of planting reached maximum values of 4.68 m² m⁻². The LAI also

decreased due to variability in meteorological conditions and forest management, also reported by Rodrigues et al. (2011).

Given the importance of eucalyptus plantations in Brazil and worldwide, this study is innovative and has much to contribute in the understanding of these exchanges between the atmosphere, vegetation and the soil (Almeida et al., 2007; Stape et al., 2008; Laclau et al., 2010; Landsberg & Sands, 2011; Campoe et al., 2016). The understanding of the interactions of growth of eucalyptus trees with the environmental conditions can be applied in growth models and remote sensing methods to improve forest management (Rubilar et al., 2018). More recently, genetic programs have focused on incorporating ecophysiological analysis to understand how new genotypes may be affected by the environmental conditions (Rubilar et al., 2018).

The main differences in carbon fluxes were due to microclimate variability and forest management, mainly to variation in rainfall events, fast growth of trees (increased LAI), and finally the harvest of trees. Compared to other eucalypt plantations (Pereira et al., 2007; Cabral et al., 2011; Rodrigues et al., 2011), the highest values of carbon fluxes were found throughout the years. This is due to the better conditions for growth in the Tropics compared to other climate conditions, such as in Portugal where the climate is typically Mediterranean (Pereira et al., 2007; Rodrigues et al., 2011).

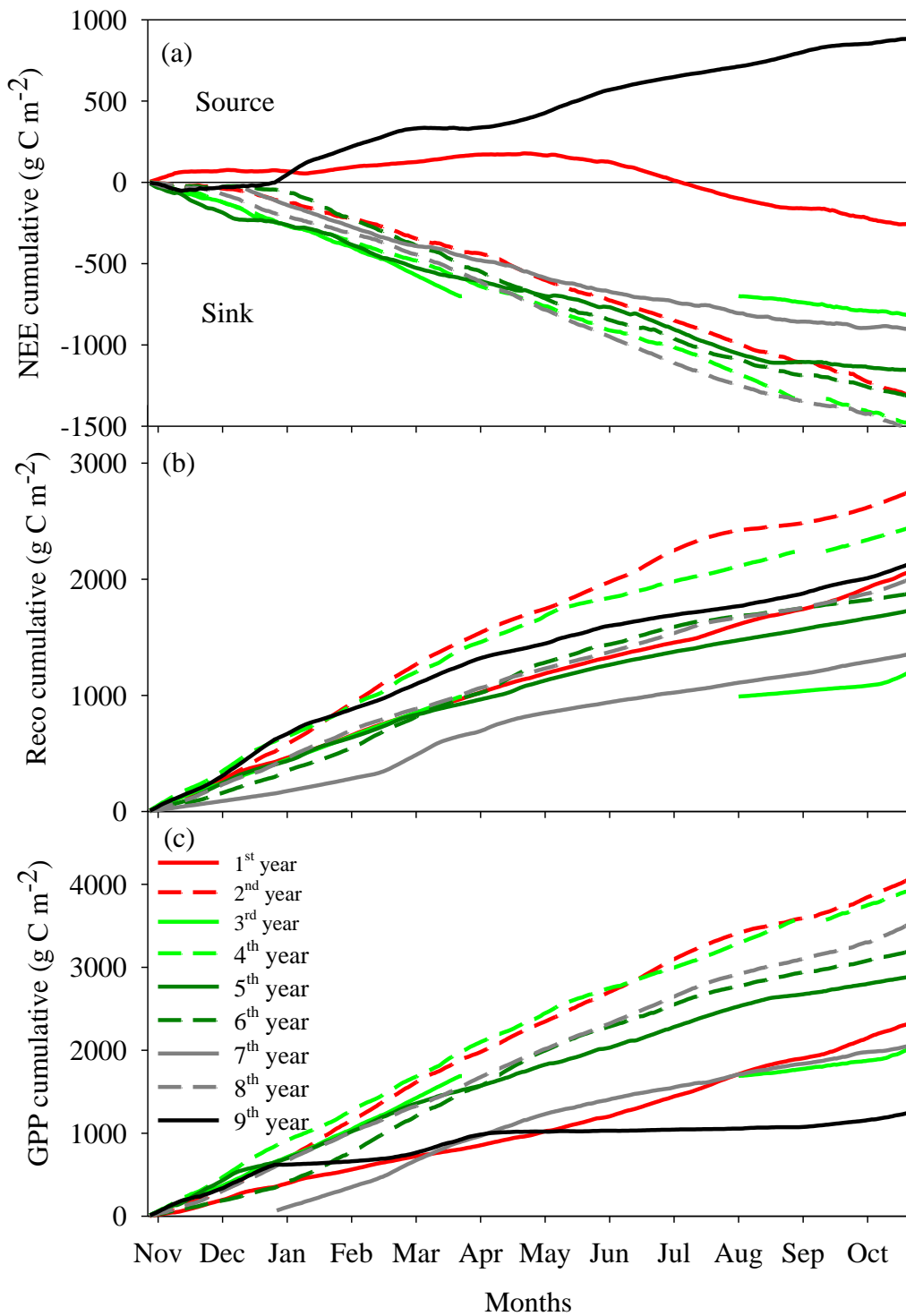


Figure 10. Annual cumulative net ecosystem exchange (NEE, g C m^{-2}), gross primary productivity (GPP, g C m^{-2}), and ecosystem respiration (Reco, g C m^{-2}) during 9 years at an eucalyptus plantation in Brazilian tropics.

Table 3. A comparison of net ecosystem exchange (NEE, g C m⁻² yr⁻¹), gross primary production (GPP, g C m⁻² yr⁻¹), and ecosystem respiration (Reco, g C m⁻² yr⁻¹) in *Eucalyptus* spp. across the world using eddy covariance technique.

Location	<i>Eucalyptus</i> spp.	Age	NEE	GPP	Reco	References
Brazil	<i>Eucalyptus grandis</i>	0 – 1	-256	2312	2055	Present study
		2 – 3	-1307	4059	2751	
		3 – 4	-819	2018	1195	
		7 – 8	-1515	3511	1995	
Portugal	<i>Eucalyptus globulus</i>	7 – 8	-861	~2100	~1300	Pereira et al. (2007)
		8 – 9	-670	~1800	~1100	
		9 – 10	-399	~1200	~800	
Brazil	<i>Eucalyptus urograndis</i>	2 – 3	-993	3108	2116	Cabral et al. (2011)
		3 – 4	-1400	3541	2142	
Portugal	<i>Eucalyptus globulus</i>	0 – 1	-11	939	928	Rodrigues et al. (2011)
		1 – 2	-200	1226	1024	
		2 – 3	-209	1294	1086	
		7 – 8	-865	2206	1340	
Australia	<i>Eucalyptus delegatensis</i>	Native Forests	-933	3200	2300	Keith et al. (2012)
Australia	<i>Eucalyptus obliqua</i> <i>Eucalyptus rubida</i> <i>Eucalyptus radiata</i>	Native Forests	-1229	-----	-----	van Gorsel et al. (2013)
Australia	<i>Eucalyptus delegatensis</i> <i>Eucalyptus dalrympleana</i>	Native Forests	-1047	-----	-----	Griebel et al. (2016)
Australia	<i>Eucalyptus obliqua</i> <i>Eucalyptus rubida</i> <i>Eucalyptus radiata</i>	Native Forests	-1046	2649	1603	Hinko-Najera et al. (2017)
			-1231	2764	1534	
			-1424	2770	1346	

The variability of the net ecosystem production (NEP = $-NEE$) during over 9 years is shown in Figure 11. The first year of plantation was observed a weak carbon sink due to short canopy vegetation, whereas with the fast growth of trees in the 2-year age was observed a high value of NEP ($\sim 80\%$ higher) (Table A1) (Cabral et al., 2011). This pattern of increase in NEP value was continued at least to 4-year age, but was observed a decline in annual NEP in the 3-year age, due to a failure in a raw data of eddy covariance measurements (~ 4 months loss), and also the rainfall cumulative for this year was lowest (986 mm). Also, was observed a strong decline in annual NEP in the 7-year age, due to low rainfall cumulative in this year (1006 mm). The eucalyptus plantation in old age presented lowest values of photosynthesis compared to young age in the same area of the study (Rody, 2013; Reis et al., 2018). However, for 8-year age was observed the highest NEP value due to higher rainfall cumulative in this year, and higher than the mean registered for this region (Alvares et al., 2013). After harvest of trees, the new planting occurred only four months later, than during this 9-year there are many events: regrowth, management and new plantation. Hence, in this first year after harvest of trees the ecosystem was a small source of carbon.

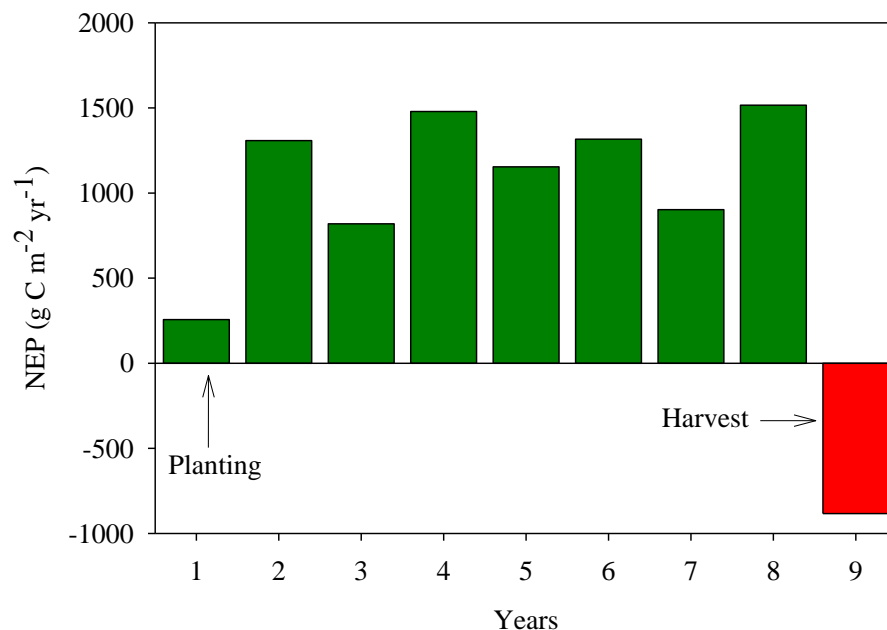


Figure 11. Net ecosystem production (NEP, $\text{g m}^{-2} \text{yr}^{-1}$) during 9 years at an eucalyptus plantation in Brazilian tropics.

4.1.3. Energy balance closure

The energy balance closure (EBC) is the relationship between the available energy ($R_n - G$) and the sum of turbulent fluxes ($H + LE$), is commonly used to validate the eddy covariance measurements (Wilson et al., 2002; Culf et al., 2004; Foken, 2008; Leuning et al., 2012; Reed et al., 2017).

During the one full rotation cycle of eucalyptus plantations occur important changes in soil cover, canopy vegetation, vertical and horizontal energy flow, thus the EBC data was evaluated into three different periods: 1) was selected the first three years of planting (Figure 12a); 2) was selected the 5, 6 and 7 years age of planting (Figure 12b); and 3) was selected the one year after the harvest of trees (including 1 year with site preparation and planting of new trees) (Figure 12c).

The closures at the 30-min time scale of the linear regression forced through the origin were to 72, 82 and 76% for the 1, 2 and 3 periods, respectively. These values were considered consistent and within the range found at eddy flux sites (Wilson et al., 2002), with an average of 84%. Cabral et al. (2010) found a high closure of energy fluxes of 102.5% in eucalyptus plantations in southeast of Brazil. Leuning et al. (2005) found a closure of 90% over a temperate *Eucalyptus* forest in Australia, using gap-filled hourly data.

Possible reasons for energy imbalance include sampling, e.g.: instruments footprint contribution, instruments bias, e.g.: net radiometer and soil heat flux measurements, neglected energy sinks, e.g.: energy storage within biomass and canopy air space, energy storage above soil heat plates (Wilson et al., 2002; Leuning et al., 2012; Reed et al., 2017). Also, was observed a loss of data during the rain periods due to open-path gas analyzer, thus contributed to underestimation H and LE fluxes. Forest management and climate variability can contribute with energy imbalance (Sun et al., 2010).

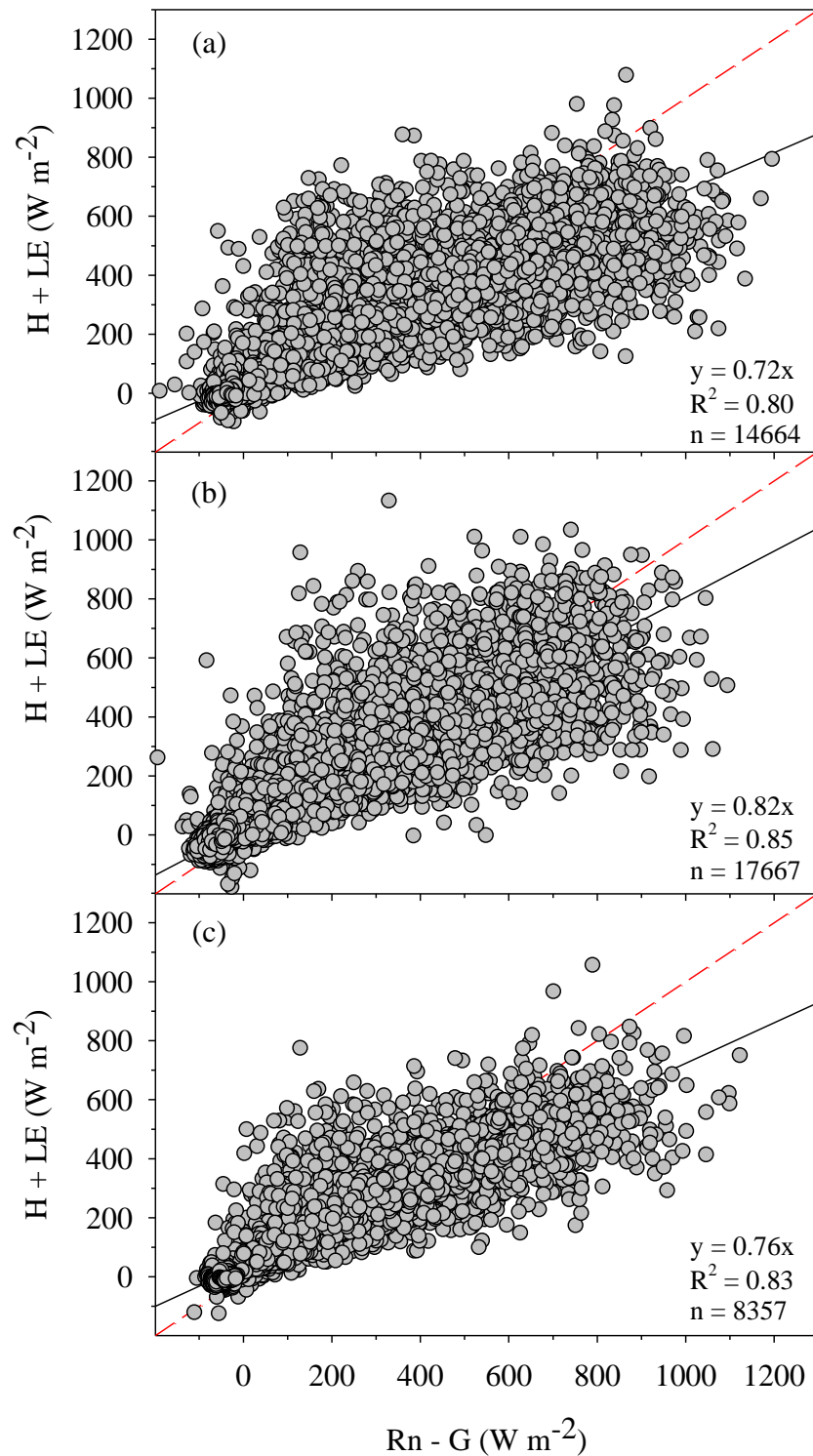


Figure 12. Energy balance closure of 30-min values of net radiation minus soil heat flux ($R_n - G$) plotted against the sum of sensible and latent heat fluxes ($H + LE$), (a) 1-2-3 years age; (b) 5-6-7 years age ; and (c) after harvest of trees. The hourly values were calculated using filtered, but not gap-filled 30-min data.

Energy balance of hourly mean values of net radiation (Rn), latent heat flux (LE), sensible heat flux (H), and soil heat flux (G) are shown in Figure 13. Plots of Rn, LE, H and G describe typical daily patterns of sensible and latent heat transfer, with maximal fluxes at solar noon.

The maximum Rn was almost similar at the 1 period (557 W m^{-2}), at the 2 period (548 W m^{-2}), and at the 3 period (492 W m^{-2}). However the LE, H and G fluxes differed across periods. The LE fluxes were quite similar in the 1 (301 W m^{-2}) and 2 (309 W m^{-2}) periods, hence was 33% lower in the 3 period (205 W m^{-2}). In contrast, the maximum H fluxes were quite similar in the 1 (141 W m^{-2}) and 2 (163 W m^{-2}), hence was 27% higher in the 3 period (223 W m^{-2}). Finally, the G fluxes were highest in the 1 (53 W m^{-2}) and 3 (69 W m^{-2}), and G fluxes were lowest in the 2 (23 W m^{-2}) period (Figure 13).

Fluxes of LE and H are similar in 1 and 2 periods (Figure 13a and b), but LE declined and H increased in the 3 periods (Figure 13c). This difference was mainly due to after harvest of trees the area stayed without vegetation, after which the regrowth started to rise and the planting of new trees. The G values reached highest values in the beginning of growth (Figure 13a) and after harvest of trees (Figure 13c), this pattern was due to less cover of soil during these periods, wherein favored the energy input to the ground. In general, the all components of energy balance followed the same diurnal curve pattern, wherein, observed an increase in all components values after the sun-rise (> 6 h) and a decrease after the sun-down (> 18 h).

Overall, the LE dominated the energy balance in the 1 and 2 periods, and after harvest of trees the H dominated the energy balance (Table A3). The mean LE/Rn ratio was 0.71 ± 0.15 and 0.65 ± 0.15 for 1 and 2 periods respectively, and the LE/Rn was lowest in the 3 period, with 0.51 ± 0.15 . On the other hand, the mean H/Rn ratio was higher in the 3 period (0.54 ± 0.18) compared to 1 (0.27 ± 0.12) and 2 (0.24 ± 0.15) periods. The soil heat flux (G) was the lowest component in the energy balance, with mean G/Rn ratio of 0.01 for all periods (Table A3).

The mean Bowen ratios β (H/LE) value was equal for 1 and 2 periods (0.43 ± 0.27 and 0.43 ± 0.34 , respectively) and the β was very high for 3 period (1.25 ± 0.15) (Table A3). The major difference in β across periods was due to highest values of H in the 3 period and a reduction in leaf area index (Cabral et al., 2010; Sun et al., 2010). Rodrigues et al. (2011) found an average 0.55 to 1.70 of Bowen ratio in a Portuguese eucalypt stand under two main events: drought and harvest of trees.

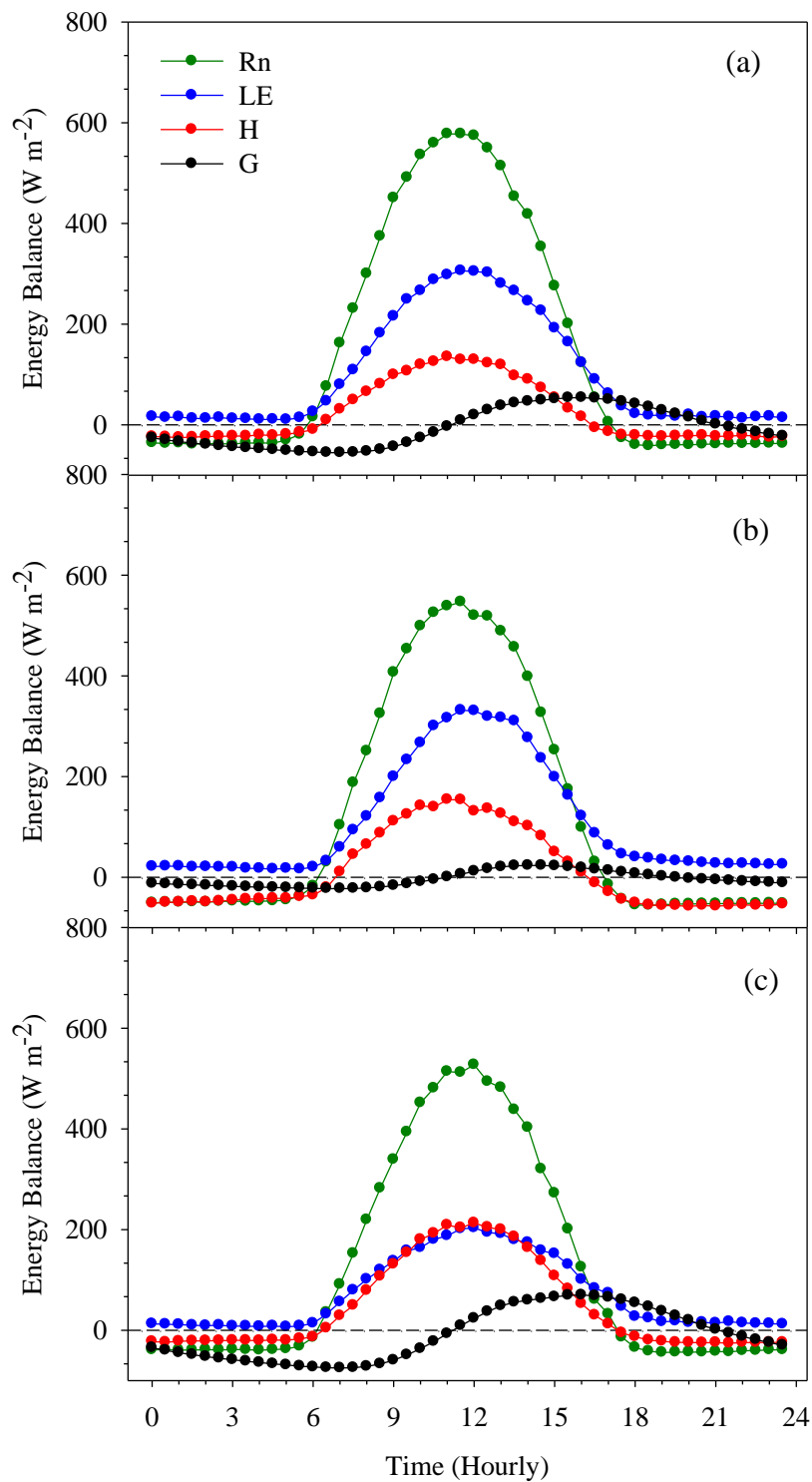


Figure 13. Hourly mean values of net radiation (Rn), latent heat flux (LE), sensible heat flux (H), and soil heat flux (G). (a) 1-2-3 years age of planting; (b) 5-6-7 years age of planting; and (c) after harvest of trees. Note: the hourly values were calculated using filtered, but not gap-filled 30-min data.

4.1.4. Evapotranspiration, water-use efficiency, and canopy conductance

Daily sum of evapotranspiration (ET, mm day⁻¹), canopy conductance (g_c , mm s⁻¹), water-use efficiency (WUE, g C kg⁻¹ H₂O⁻¹), and intrinsic water-use efficiency (WUE_i, g C kg⁻¹ H₂O⁻¹) during the spanning one full rotation cycle of eucalypt plantation are shown in Figure 14. Similar to pattern of carbon fluxes across all years (Figure 9), the daily sum of ET, g_c , WUE, and WUE_i consistently peak in summer season (December to March), and decline in winter season (June to September).

The daily ET ranged between 0.05 to 7.84 mm day⁻¹, with average of 3.3 ± 1.4 (Figure 14a). Following the ET seasonal pattern the mean daily canopy conductance (g_c) ranged between 0.5 to 50.7 mm s⁻¹, with average of 5.6 ± 3.9. After harvest of trees, the mean daily g_c was extremely low (~0 mm s⁻¹). Some spikes observed in g_c are due to very low values of vapor pressure deficit (VPD) entire the study period (Figure 14b). The daily WUE, defined as the ratio of GPP to ET, ranged between 0 to 17.5 g C kg⁻¹ H₂O⁻¹, with average of 2.5 ± 1.2 (Figure 14c). The daily WUE_i, defined as the ratio of GPP to g_c , ranged between 0 to 140.3 g C kg⁻¹ H₂O⁻¹, with average of 21 ± 13 (Figure 14c).

In general, the annual evapotranspiration presented a varied by 56% to 122% of the annual rainfall (ET/Rainfall), with an annual average of 93% ± 19 (Table A4). These results are consistently with 82% and 96% found by Cabral et al. (2010) for eucalyptus plantations over a two year period, and 95% found by Almeida et al. (2007) for *Eucalyptus grandis*, both in Brazil. The ET/Rainfall ranged from 63% to 191%, with an average of 107% ± 42, over eight years in stands of eucalypt in Portugal; and 66% obtained by Maier et al. (2017) for nine-year-old eucalypts in the southern United States. The eucalyptus species are fast growing, mainly for first four years of growing, therefore was observed use more of water from the ecosystem, thus can be indicating that water was removed from the soil to maintain the high transpiration rates (Whitehead & Beadle, 2004; Cabral et al., 2010).

Although the annual water consumption was higher in these years (2 and 4 year age), was observed higher resource use-efficiency and canopy conductance, with maximum values of WUE ($3.8 \text{ g C kg}^{-1} \text{ H}_2\text{O}^{-1}$); WUE_i ($30.4 \text{ g C kg}^{-1} \text{ H}_2\text{O}^{-1}$); and g_c (6.7 mm s^{-1}) (Table A4). These maximum values were coupled with maximum annual gross primary production ($\text{GPP} = 4059 \text{ g C m}^{-2} \text{ yr}^{-1}$, Table A1), indicating highest rates of photosynthesis by eucalypt trees.

Water use efficiency relates productivity and water consumption, and fast growing of eucalyptus plantations generally has high WUE (Stape et al. 2004). Overall, the values of resource use-efficiency in this study were higher compared to other studies with eucalyptus plantations. Maier et al. (2017) reported that despite the eucalyptus used more water than pine, the WUE in eucalyptus (2.86) was greater compared to pine (1.72). Monthly annual average of WUE varied by 2.75 to $4.84 \text{ g C kg}^{-1} \text{ H}_2\text{O}^{-1}$ in a Portuguese eucalypt stand according to Rodrigues et al. (2011).

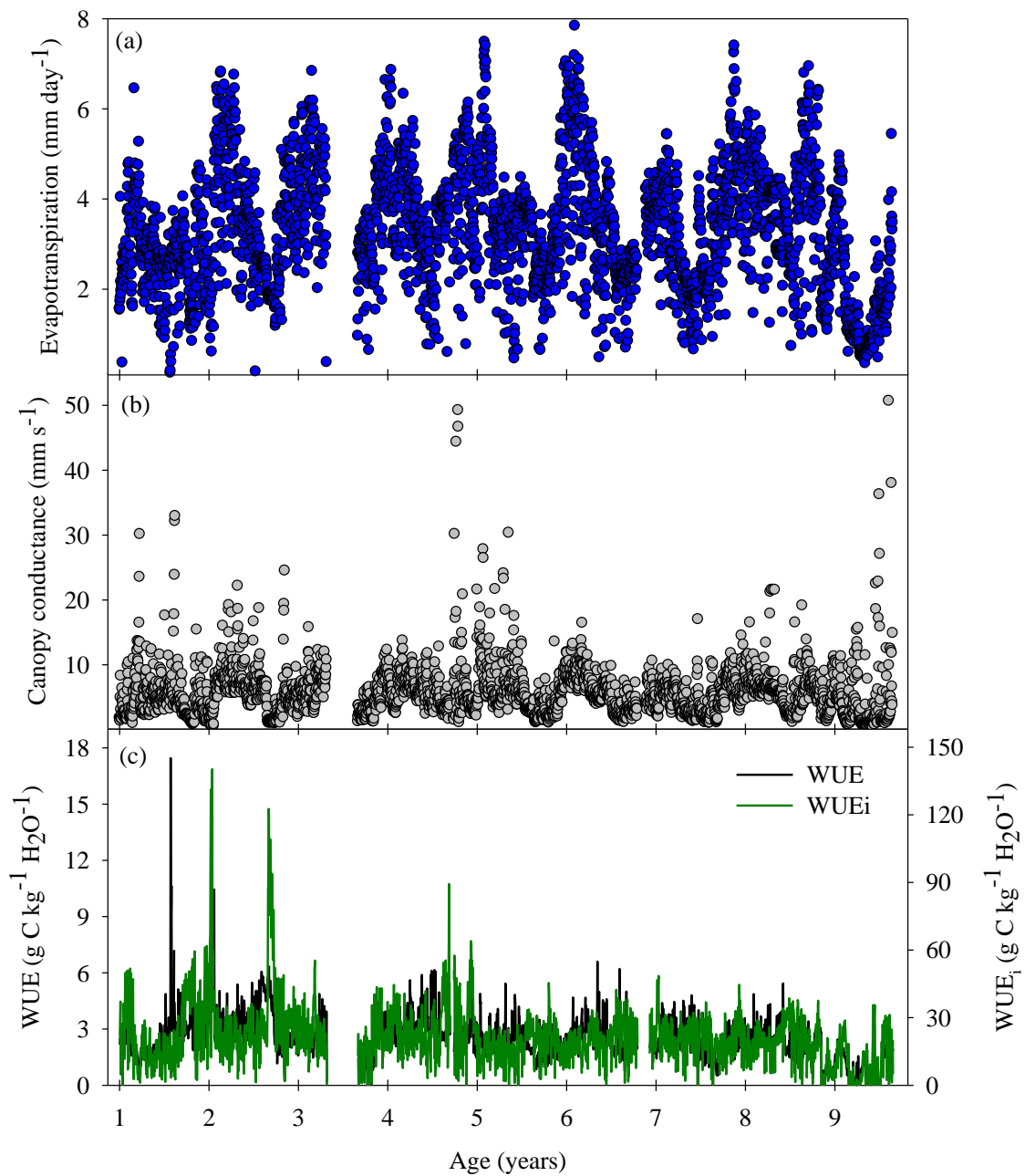


Figure 14. Daily evapotranspiration (ET, mm day⁻¹) (a), mean daily canopy conductance (g_c , mm s⁻¹) (b), mean daily water use-efficiency (WUE, g C kg⁻¹ H₂O⁻¹) (c, left), and mean daily intrinsic water use-efficiency (WUE_i, g C kg⁻¹ H₂O⁻¹) (c, right) during 9 years at an eucalyptus plantation in Brazilian tropics.

Canopy conductance (g_c) was plotted as a function of water vapor pressure deficit (VPD) in Figure 15 during the spanning one full rotation cycle of eucalypt plantation. During the study period, g_c decrease with increasing in VPD, but more strongly when $VPD > 1.5$ kPa, evidencing a stomatal regulation by environmental conditions. Decrease in g_c due to higher VPD was reported by Cabral et al. (2010) in eucalyptus plantations in Brazil. Reis et al. (2018) observed an strongly reduction in stomatal conductance for young and mature eucalyptus plantations during the dry period in the same study area.

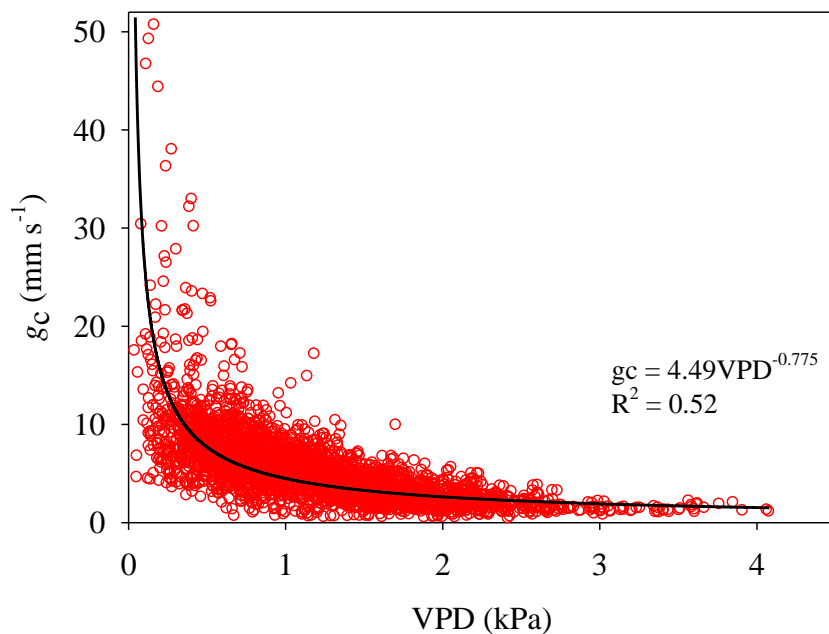


Figure 15. Scatter plot of mean daily canopy conductance (g_c , mm s^{-1}) by mean daily water vapor pressure deficit (VPD, kPa).

4.2. Second study: Comparative of Eucalypt and Savanna ecosystems

The study encompasses two ecosystem sites in Mato Grosso do Sul state: *Eucalyptus* plantations (EUC) and Savanna biome (SAV) during December 2012 to August 2013. The goal was to characterize the biogeophysical functioning of each of these forest types, and the likely impacts of land use change from native mixed-species savanna to eucalypt plantation.

4.2.1. Microclimate

The wind rose diagram show that the prevailing surface winds are from the west for SAV (mean of 180.8 °) and the southeast for EUC (mean of 136.9 °) during the study period (Figure 16). The wind speed (WS) values ranged between 0.03 to 5.97 m s⁻¹, with an average of 1.46 m s⁻¹ ± 0.83 for SAV ecosystem (Figure 16a), and the WS ranged between 0.03 to 3.67 m s⁻¹, with an average of 1.56 m s⁻¹ ± 0.60 for EUC ecosystem (Figure 16b). The reduction in WS during the dry period is consistent with findings of Giambelluca et al. (2009) in two different Brazilian savanna sites.

The greater variability in wind direction distribution in the savanna ecosystem may be explained by the heterogeneous and discontinuous vegetative canopy, mainly in dry periods due to leaf senescence wherein observed a decline in 50% of leaf area index (LAI) (Figure 17). Also, this variation in landscape around the tower may have contributed to maximum values of wind speed (38% highest) observed in savanna ecosystem. Miranda et al. (1997) reported enhanced in air movement due to reduce in amount of leaves during the dry periods in Brazilian savanna (*cerrado sensu stricto*).

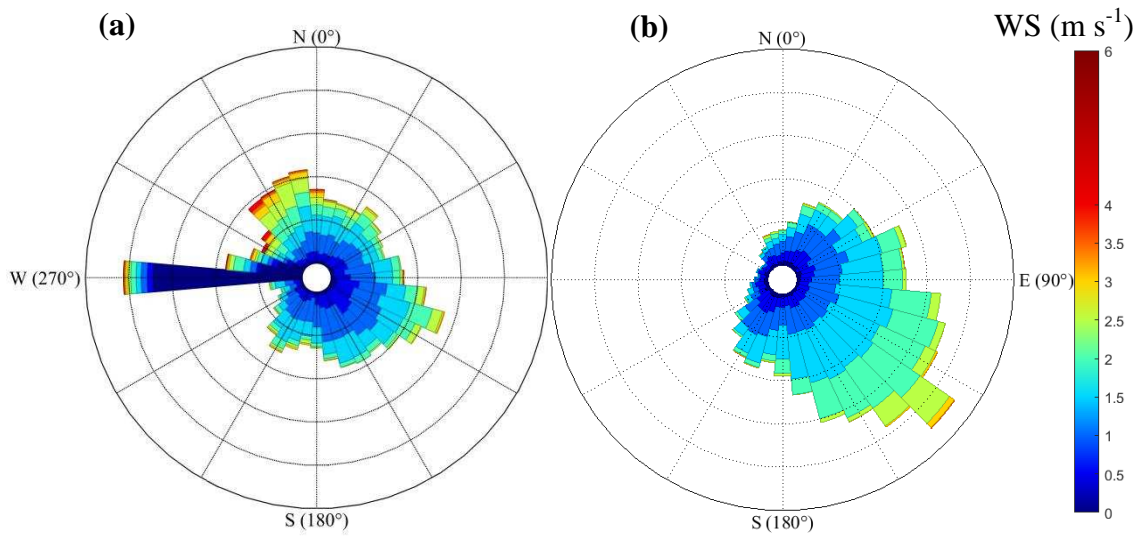


Figure 16. Prevailing wind direction (degrees) and wind speed (WS, m s^{-1}), based on 30-minute values for savanna ecosystem (a) and eucalyptus plantations (b) at 20 m and 36 m above the ground, respectively.

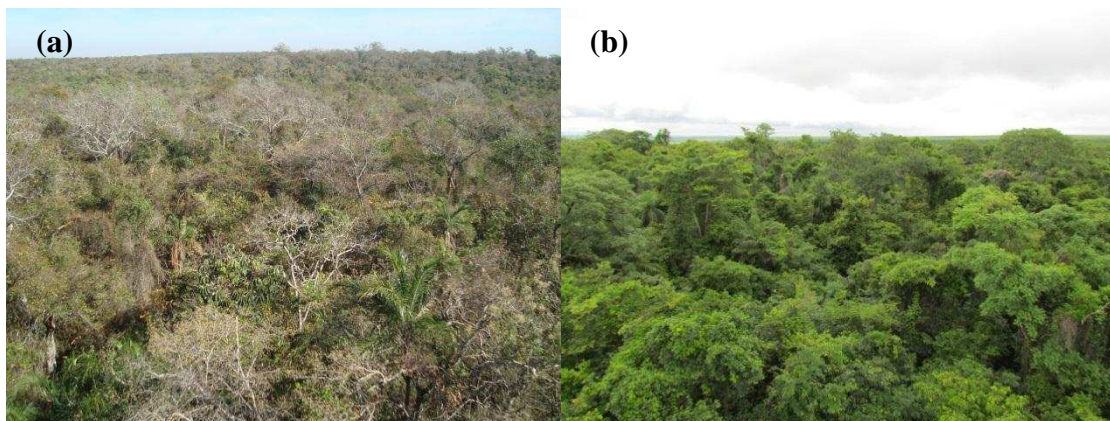


Figure 17. Leaf area index (LAI) at the savanna ecosystem during the dry (a, $\text{LAI} = 1.9 \text{ m}^2 \text{ m}^{-2} \pm 0.3$) and wet (b, $\text{LAI} = 3.8 \text{ m}^2 \text{ m}^{-2} \pm 0.4$) seasons in Brazilian tropics. Standard deviation indicate \pm SD.

Daily microclimate and soil water content time series during December 2012 to August 2013 in an eucalypt plantation (EUC) and in a native Savanna forest (SAV) are shown in Figure 18. During the study period the air temperature (T_{air} , mean of 23 °C), photosynthetic active radiation (PAR, mean of 34 mol m⁻² day⁻¹), and rainfall cumulative (sum of 1013.5 mm) were similar among the two ecosystems (Figure 18a, c and e). In contrast, the vapor pressure deficit (VPD) was lower in SAV ecosystem (mean of 0.74 kPa ± 0.42) than EUC ecosystem (mean of 0.96 kPa ± 0.50) throughout the study period (Figure 18b). Soil water content (SWC) was slightly higher in SAV ecosystem (mean of 0.81% ± 0.16) than EUC ecosystem (mean of 0.78% ± 0.18) during March to August 2013 (Figure 18d). The rainfall at both ecosystems reaching the maximum of 80 mm day⁻¹ in April, with average of 3.8 mm day⁻¹ (Figure 18e).

The daily pattern of T_{air} was well correlated with PAR at all study period at both ecosystems, but was observed minimum peaks in T_{air} during the dry period (July to August), wherein T_{air} dropped to 7.8 °C at the EUC ecosystem and 10.0 °C at the SAV ecosystem, both in July. This decline in T_{air} showed more related to water availability than PAR, also reported in other forests (Giambelluca et al., 2009; Sun et al., 2010). Consequently, the VPD fluctuation also was tightly related to water amount of water available in the environment, with a highest peak of 2.8 kPa at the EUC ecosystem and 2.2 kPa at the SAV ecosystem, both in dry period (August 2013).

The rainfall events showed a clear seasonal variability at both ecosystems, evidencing a strong wet (December to April, 843 mm) and dry period (May to August, 170 mm). These rainfall events resulting in higher soil water content from December 2012 to April 2013 than the all entire study period (Figure 18). The LAI varied according to water availability, reached 4.8 and 3.8 m² m⁻² during the wet period for EUC and SAV ecosystems, respectively. During the dry period the LAI decline in 32% and 50% for EUC (3.23 m² m⁻²) and SAV (1.9 m² m⁻²) ecosystem, respectively.

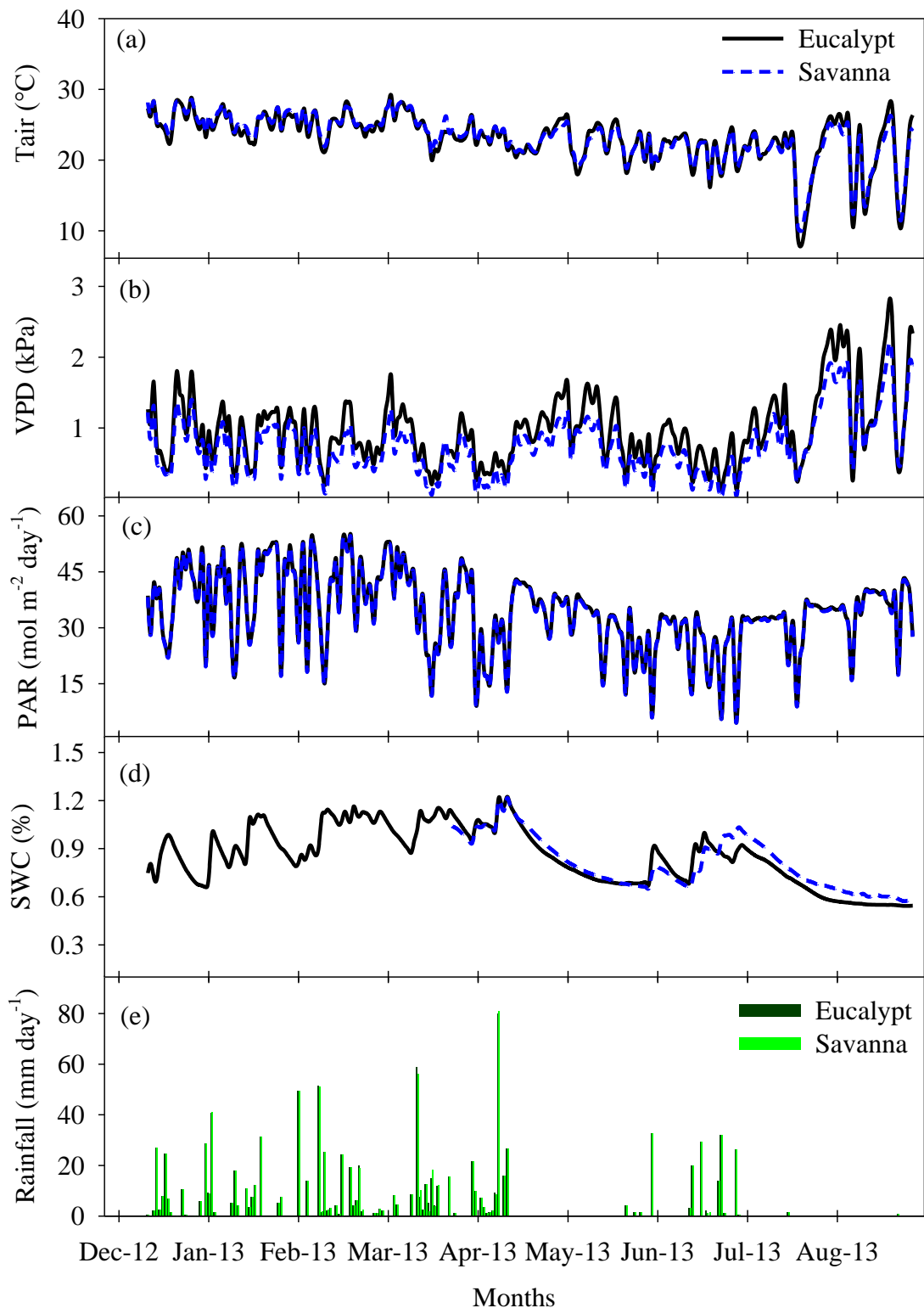


Figure 18. Time series of mean daily values of air temperature (T_{air} , $^{\circ}\text{C}$), vapor pressure deficit (VPD, kPa), daily cumulative photosynthetically active radiation (PAR, $\text{mol m}^{-2} \text{ day}^{-1}$), mean daily values of soil water content (SWC, %), and daily cumulative of rainfall (mm day^{-1}) at the savanna ecosystem and eucalyptus plantations in Brazilian tropics.

4.2.2. Carbon fluxes

The time series of half-hourly CO₂ flux ($\mu\text{mol m}^{-2} \text{s}^{-1}$) during December 2012 to August 2013 in an eucalypt plantation (EUC) and in a native Savanna forest (SAV) are shown in Figure 19. According to environmental conditions (Figure 18), during the wet period (December 2012 to April 2013) the CO₂ fluxes range between -53.2 to $45.1 \mu\text{mol m}^{-2} \text{s}^{-1}$, compared to -31.6 to $38.4 \mu\text{mol m}^{-2} \text{s}^{-1}$ in the dry period (May to August 2013) at the SAV ecosystem (Figure 19a).

At the EUC ecosystem the CO₂ fluxes range between -49.8 to $26.2 \mu\text{mol m}^{-2} \text{s}^{-1}$ in wet period, compared to -47.7 to $22.3 \mu\text{mol m}^{-2} \text{s}^{-1}$ in the dry period (Figure 19b). In SAV ecosystem the amplitude in CO₂ flux (45.1 to $-53.2 \mu\text{mol m}^{-2} \text{s}^{-1}$, range of $98.3 \mu\text{mol m}^{-2} \text{s}^{-1}$) was very higher compared to CO₂ flux (26.2 to $-49.8 \mu\text{mol m}^{-2} \text{s}^{-1}$, range of $76 \mu\text{mol m}^{-2} \text{s}^{-1}$) in EUC ecosystem (Figure 19a and b). The CO₂ flux variation in SAV ecosystem was really big, due to high diversity of species in this ecosystem, thus favored a high variability in atmospheric dynamic. Although apparently the photosynthesis was high, the ecosystem respiration was extremely high throughout the study (Figure 19a).

The CO₂ flux in EUC ecosystem was tightly coupled with rainfall events and soil moisture, wherein in dry period (~ May and August 2013) was verified a decrease of 21% in CO₂ fluxes. In July was observed an important rain event, on what favored an increase in CO₂ fluxes, indicating that eucalyptus species have high response to environmental conditions also related by Reis et al. (2018) in diurnal patterns of net photosynthesis rate in the same study area with eucalyptus plantations. In contrast, this fast response to environmental conditions was not observed in savanna ecosystem (Reis et al. 2018), due to adaptive evolution of these species.

Although was observed a strong peak coupled with heavy rain events in SAV ecosystem (April 2013), after this period the CO₂ flux declined to entire dry period (May to August 2013). This reduction in CO₂ flux was related with decline in soil moisture, decrease in LAI and increase in VPD, also reported in other savanna ecosystems (da Rocha et al. 2002; Vourlitis et al., 2001; Giambelluca et al. 2009; Cabral et al., 2015; Oliveira et al., 2015; Reis et al. 2018).

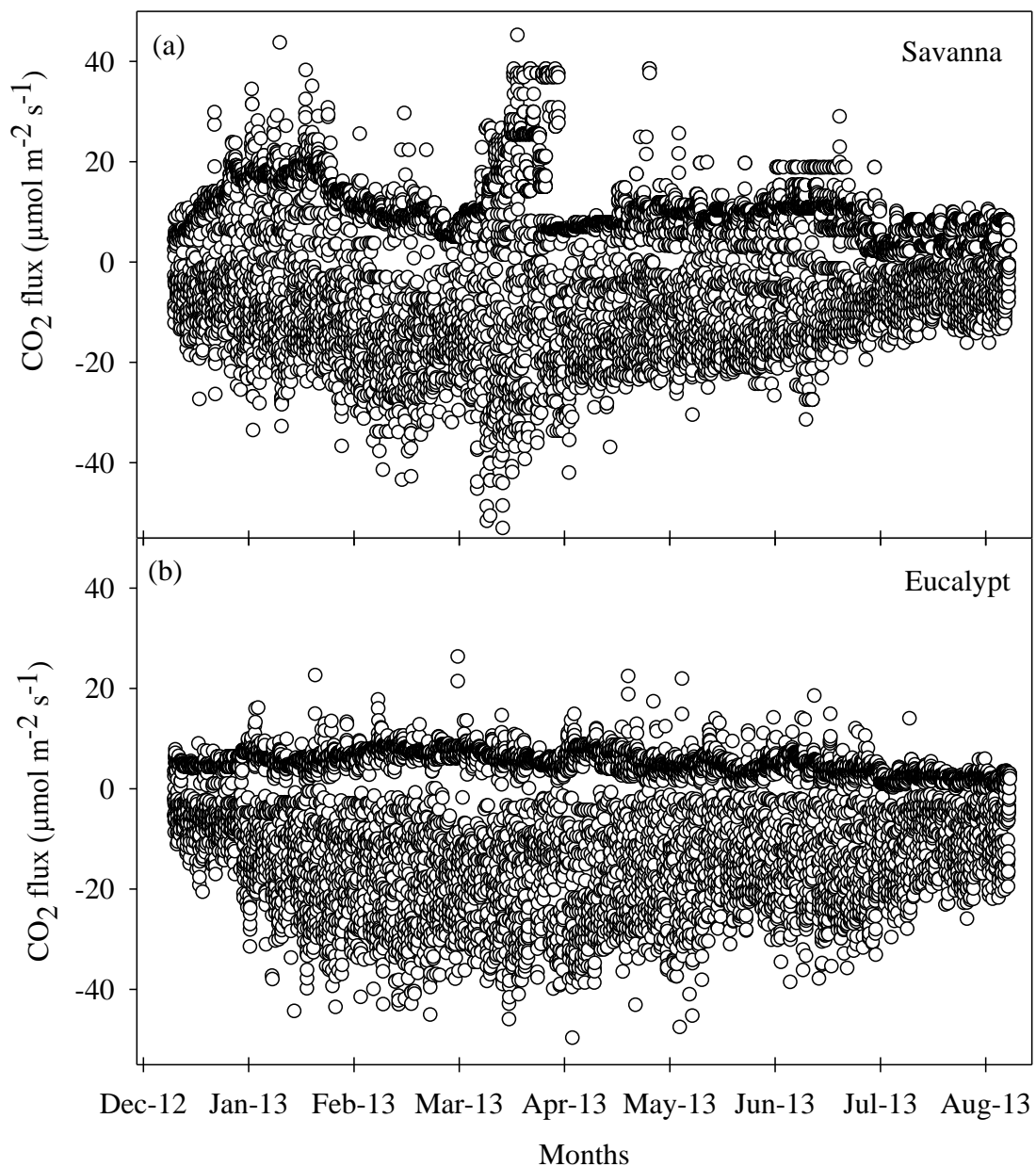


Figure 19. Time series of half-hourly CO₂ flux ($\mu\text{mol m}^{-2} \text{s}^{-1}$) in a savanna ecosystem (a) and eucalyptus plantations (b) in Brazilian tropics. Positive values of CO₂ flux represent a release of CO₂ from the ecosystem into the atmosphere, and negative values of CO₂ flux denote uptake of CO₂ by the ecosystem.

The daily integration of CO₂ flux partitioned in net ecosystem exchange (NEE), gross primary production and ecosystem respiration (Reco) at both ecosystems are show in Figure 20.

The daily NEE ranged between 14.3 to -4.7 g C m⁻² day⁻¹ for SAV ecosystem, and 4.2 to -9.9 g C m⁻² day⁻¹ for EUC ecosystem (Figure 20a and b), negative NEE denotes the net carbon uptake of the ecosystem. Positive NEE was observed in the most of study period for SAV ecosystem (Figure 20a). Daily GPP ranged between 2.55 to 32.6 g C m⁻² day⁻¹ for SAV ecosystem, and 1.6 to 18.3 g C m⁻² day⁻¹ for EUC ecosystem (Figure 20a and b). The daily Reco ranged between 2.3 to 34.9 g C m⁻² day⁻¹ for SAV ecosystem, and 1.1 to 11.2 g C m⁻² day⁻¹ for EUC ecosystem (Figure 20a and b).

Despite was observed high values in GPP also was observed high values for Reco at SAV ecosystem (Figure 20a). In April 2013, was observed a high peak in the GPP and Reco fluxes at SAV ecosystem (Figure 20a), largely due to intense rains in late March and at the beginning April 2013 (Figure 18e). These intense rain events may have contributed to filled all soil pores, wherein expelled the CO₂ gas from the soil to atmosphere. Vasconcelos (2014) reported that the total CO₂ effluxes at soil surface were seven times higher in the rainy period compare to dry period at the same savanna ecosystem.

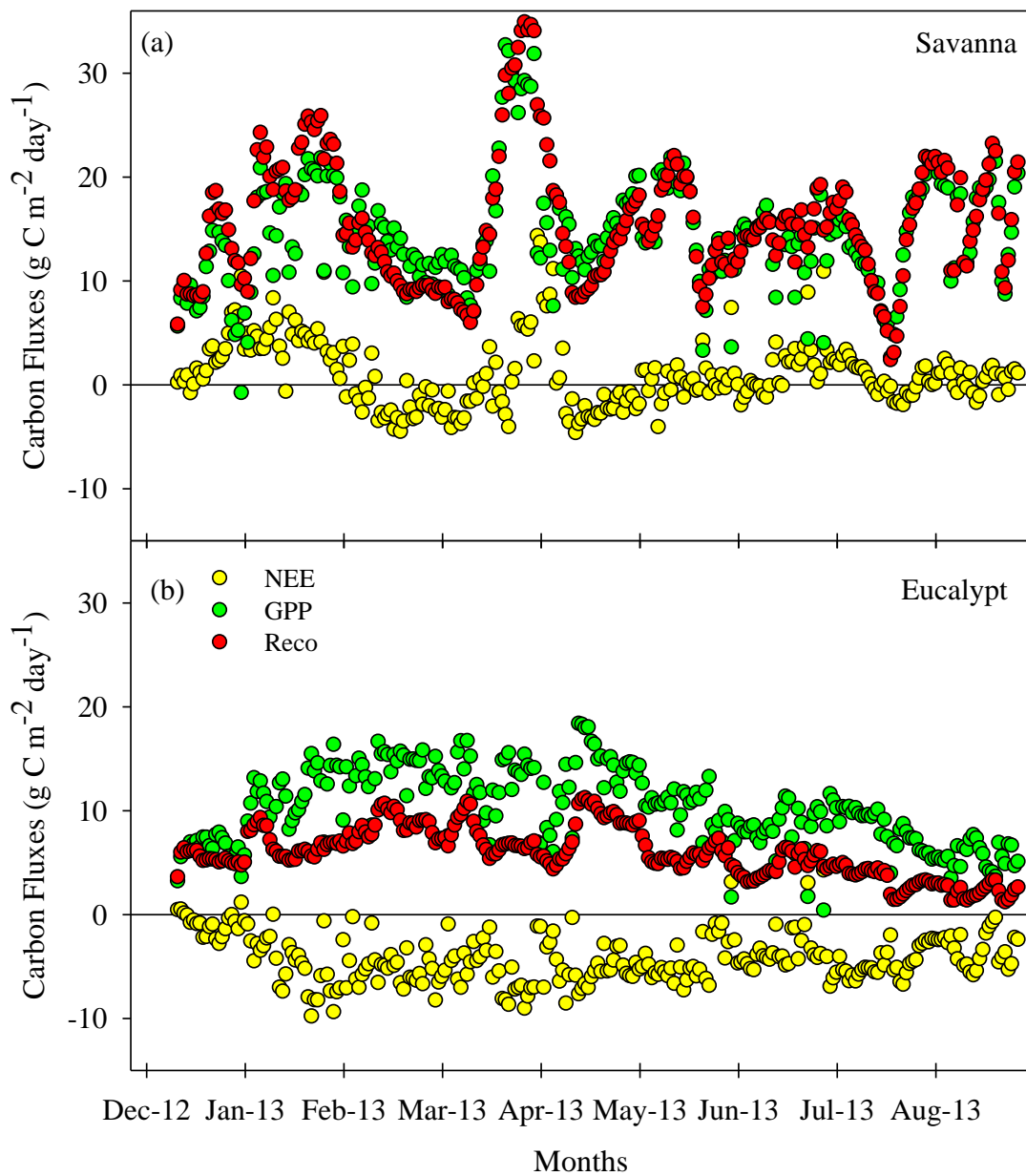


Figure 20. Time series of daily carbon fluxes: net ecosystem exchange (NEE, g C m⁻² day⁻¹), gross primary production (GPP, g C m⁻² day⁻¹), and ecosystem respiration (Reco, g C m⁻² day⁻¹) in a savanna ecosystem (a) and eucalyptus plantations (b) in Brazilian tropics.

4.2.3. Seasonality of carbon fluxes

The monthly sum of NEE, GPP and Reco are show in Table A5. Across all months, the eucalypt ecosystem was carbon sink (negative NEE) (Table A5, Figure 21a). Although, the SAV ecosystem was carbon sink in a few months (Feb, Mar and May 2013), even so the NEE cumulative in SAV ecosystem throughout the study period showed a carbon source (Figure 21a).

The sum of GPP was 2678 g C m⁻² for EUC ecosystem, whereas the sum of Reco was 1542 g C m⁻² during the study period. However, the sum of GPP was 3833 g C m⁻² (30% higher than EUC) for SAV ecosystem, and the sum of Reco was 4080 g C m⁻² (62% higher than EUC) taking to an ecosystem carbon source (Table A5). The GPP and Reco cumulative throughout the study period are show in Figure 21b and c. Overall, the savanna ecosystem was small carbon source to atmosphere (246.9 g C m⁻²) during the study period, while the eucalypt ecosystem was strong carbon sink (-1136.8 g C m⁻²) (Table A5, Figure 21a). Thus, the ratio of GPP/Reco was 0.94 and 1.74 in savanna and eucalypt ecosystem, respectively indicating greater respiration at SAV ecosystem.

The limited data due to failure of system do not allow calculation of the annual net ecosystem exchange of the savanna ecosystem. The results demonstrated that savanna ecosystem is a carbon source from the ecosystem to atmospheric, releasing about 2.5 t C ha⁻¹ over the study period (9 months). According to da Rocha et al. (2002) that annual sum of NEE in the Cerrado *sensu stricto* was small sink of 0.1 t C ha⁻¹.

Therefore, these amounts of data are not enough to define if this savanna ecosystem is a carbon source entire the time, future research are need with more eddy covariance measurements to ensure about the carbon contribution in this savanna ecosystem. Otherwise, compared to fast-growth of eucalypt demonstrated a strong carbon sink from the atmospheric to ecosystem, sequestering about 11 t C ha⁻¹ over the study period (9 months).

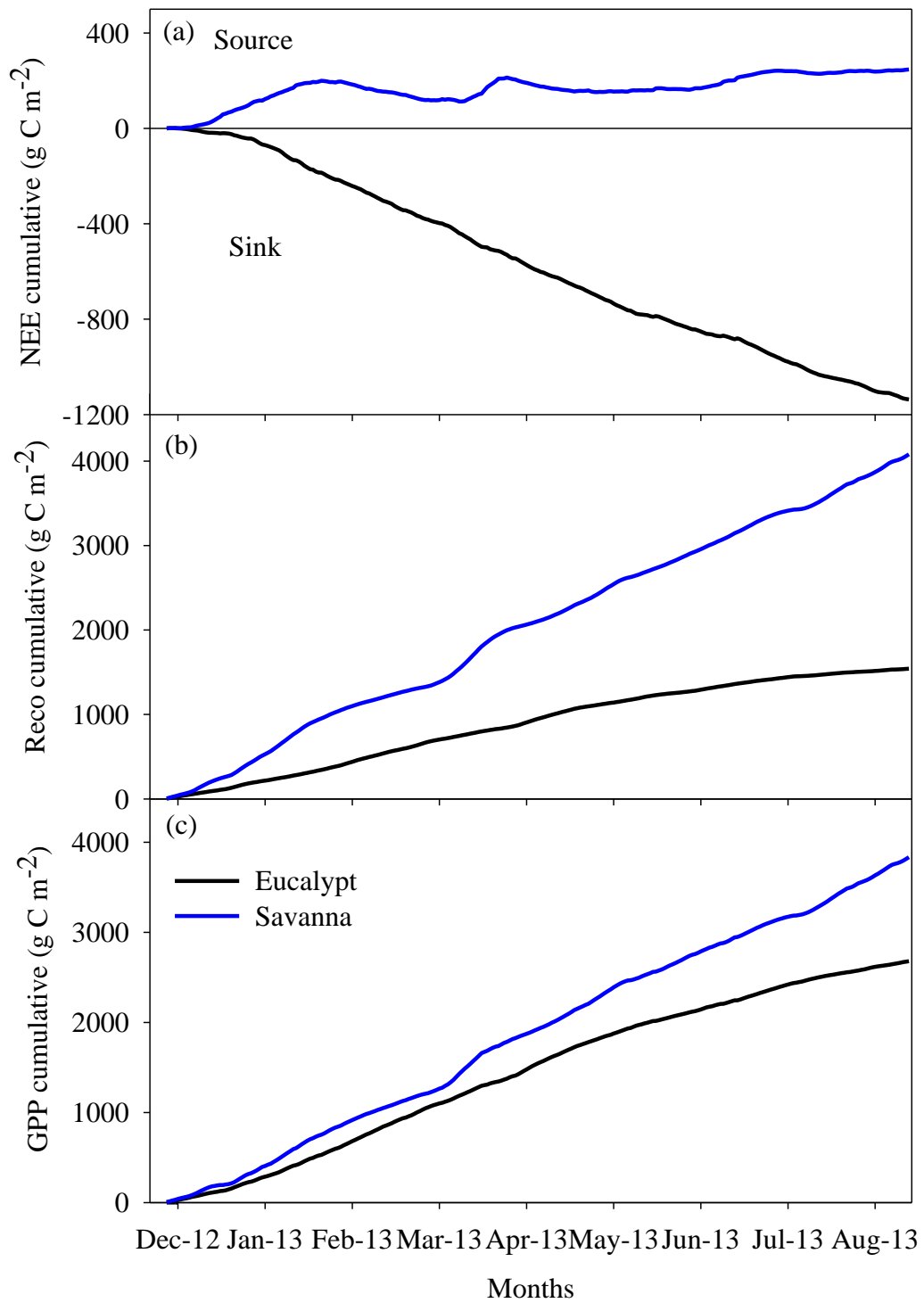


Figure 21. Cumulative net ecosystem exchange (NEE, g C m^{-2}) (a), gross primary productivity (GPP, g C m^{-2}) (b), and ecosystem respiration (Reco, g C m^{-2}) (c) at the savanna ecosystem and eucalyptus plantation in Brazilian tropics.

4.2.4. Energy balance closure

The energy balance closure was used to assess the accuracy of the eddy covariance measurements (Wilson et al., 2002; Reed et al., 2017) and can be estimate by the relationship between the available energy ($R_n - G$) and the sum of turbulent fluxes ($H + LE$).

The closures at the 30-min time scale of the linear regression forced through the origin were to 83 and 78% for the SAV and EUC ecosystems, respectively (Figure 22a and b). These values were considered consistent and within the range found at eddy flux sites with savanna ecosystems: 92% in savanna ecotone in Brazil by Vourlitis et al. (2001); 77 and 84% in Brazilian savannas by Giambelluca et al. (2009); 70% in *sensu-stricto* savanna in southeast Brazil by da Rocha et al. (2009); and 99% in *sensu-stricto* savanna in southeast Brazil by Cabral et al. (2015). Also, for eucalypt ecosystems (Leuning et al., 2005; Cabral et al., 2010; see First study).

The energy imbalance closure could be explained by sampling, instrumentation, horizontal and vertical advection fluxes, and neglected energy sinks (Wilson et al., 2002). For savanna ecosystem the imbalance was mainly due to neglected energy stored in biomass and canopy air below the measurement height (da Rocha et al., 2009), considering this type of dense savanna. However, Giambelluca et al. (2009) reported that the energy fluxes stored in biomass and canopy air space could close to zero over entire day, thus could not contribute much to energy closure error.

Typical hourly energy balance in net radiation (R_n , $W\ m^{-2}$), latent heat flux (LE , $W\ m^{-2}$), sensible heat flux (H , $W\ m^{-2}$), and soil heat flux (G , $W\ m^{-2}$) at both ecosystems are show in Figure 22c and d. Plots of R_n , LE , H and G describe typical daily patterns of sensible and latent heat transfer, with maximal fluxes at solar noon. The maximum R_n was almost identical at the savanna ecosystem ($562\ W\ m^{-2}$) and at the eucalypt ecosystem ($540\ W\ m^{-2}$). The maximum LE flux was 8% lower at the savanna ecosystem ($338\ W\ m^{-2}$) than at the eucalypt ecosystem ($368\ W\ m^{-2}$). In contrast, the maximum H flux was 40% higher at the savanna ecosystem ($208\ W\ m^{-2}$) than at the eucalypt ecosystem

(124 W m^{-2}). The maximum G flux was 63% lower at the savanna ecosystem (27 W m^{-2}) than at the eucalypt ecosystem (44 W m^{-2}). Energy partitioning showed a seasonal variability at both ecosystems (Table A6).

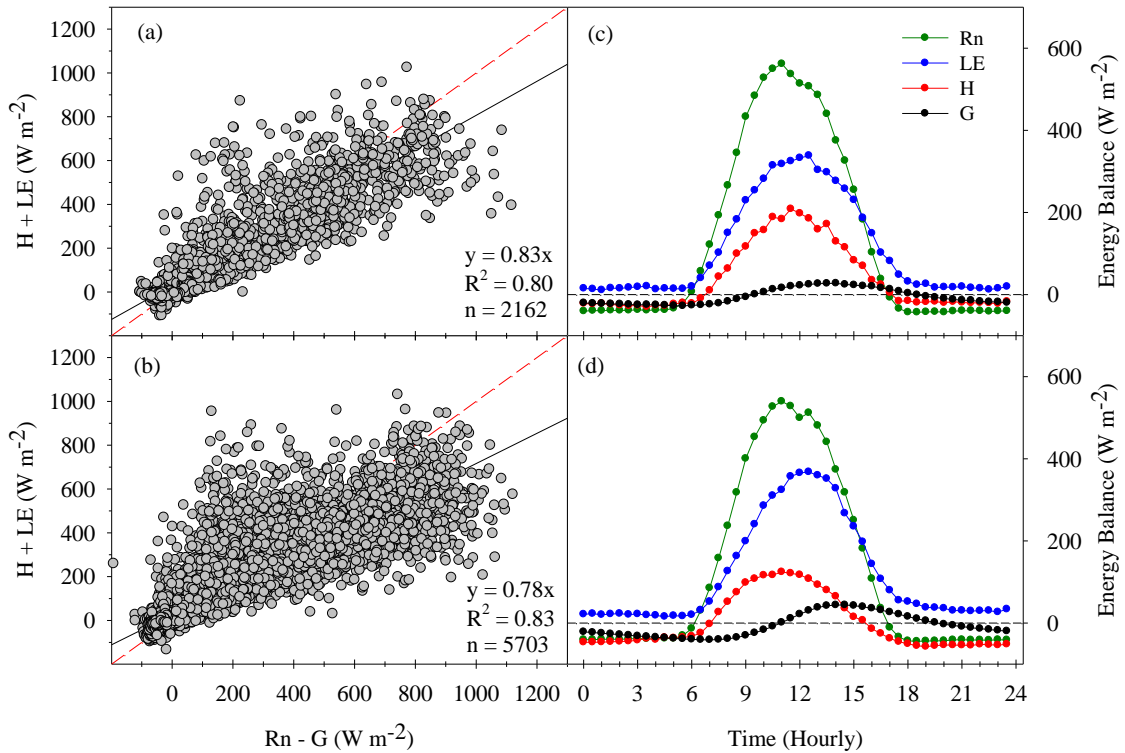


Figure 22. Energy balance closure of 30-min values of net radiation minus soil heat flux ($Rn - G$) plotted against the sum of sensible and latent heat fluxes ($H + LE$) for savanna ecosystem (a) and eucalyptus plantations (b). Note: the hourly values were calculated using filtered, but not gap-filled 30-min data. Hourly mean values of net Rn , LE , H and G in savanna ecosystem (a) and eucalyptus plantations (b) during December 2012 to March 2013 in Brazilian tropics.

Overall, the LE dominated the energy balances at both ecosystems, followed by H and G (Table A6). The mean LE/Rn ratio was 0.69 and 0.75 at the SAV and EUC ecosystems, respectively. In contrast, the mean H/Rn ratio was higher 0.33 at the SAV ecosystem compare to 0.19 at the EUC ecosystem. The soil heat flux (G) was the lowest component in the energy balances, with mean G/Rn ratio of 0.02 for both ecosystems.

The monthly mean Bowen ratios β (H/LE) values (0.50 ± 0.19) at the SAV ecosystem were higher than at the EUC ecosystem (0.30 ± 0.33). The difference between the two ecosystems was in amount of evapotranspiration (ET), wherein ET was higher at the EUC ecosystem compared to SAV ecosystem during the study period. Also, the leaf area index (LAI) dropped to 50% at the SAV ecosystem during the dry period, on what favored an increased in air temperature (sensible heat flux - H) instead water evaporation (latent heat flux - LE) (Giambelluca et al., 2009; Cabral et al., 2015).

4.2.5. Seasonality of water fluxes

Seasonal daily patterns in evapotranspiration (ET, mm day^{-1}), water use-efficiency (WUE, $\text{g C kg}^{-1} \text{H}_2\text{O}^{-1}$), canopy conductance (g_c , mm s^{-1}), and intrinsic water use-efficiency (WUE_i, $\text{g C kg}^{-1} \text{H}_2\text{O}^{-1}$) at both ecosystems are show in Figure 23. ET for SAV ecosystem ranged between 0.5 to 6.0 mm day^{-1} , with an average of $3.6 \text{ mm day}^{-1} \pm 1.0$. For EUC ecosystem ET ranged between 0.5 to 7.8 mm day^{-1} , with an average of $3.9 \text{ mm day}^{-1} \pm 1.5$. The daily ET was consistently higher for EUC ecosystem than SAV ecosystem, especially during the wet period (December 2012 to April 2013) (Figure 23a).

In contrast, the WUE was generally higher in SAV ecosystem than EUC ecosystem (Figure 23b). WUE for SAV ecosystem ranged between 1.2 to 13.9 $\text{g C kg}^{-1} \text{H}_2\text{O}^{-1}$, with an average of $4.3 \text{ g C kg}^{-1} \text{H}_2\text{O}^{-1} \pm 1.8$. For EUC ecosystem WUE ranged between 0.5 to 6.6 $\text{g C kg}^{-1} \text{H}_2\text{O}^{-1}$, with an average of $2.7 \text{ g C kg}^{-1} \text{H}_2\text{O}^{-1} \pm 0.8$. The higher values of GPP can be explaining these higher values in WUE in SAV ecosystem compared to EUC ecosystem (Reis et al., 2018).

Canopy conductance (g_c) was clear higher in SAV ecosystem than EUC ecosystem with many evidenced peaks (Figure 23c). Daily mean g_c for SAV ecosystem ranged between 2.2 to 109.5 mm s^{-1} , with an average of $12.6 \text{ mm s}^{-1} \pm 12.9$. For EUC ecosystem g_c ranged between 1.4 to 16.4 mm s^{-1} , with an average of $6.6 \text{ mm s}^{-1} \pm 2.6$.

These peaks observed in the SAV ecosystem are coupled to rain events and low values of VPD (Figure 18b and d). During the dry period (May and August 2013) the canopy conductance was extremely low for the two ecosystems. Consequently, was observed high WUE_i values during this dry period (Figure 23d). The WUE_i for SAV ecosystem ranged between 0.8 to 114.2 $\text{g C kg}^{-1} \text{ H}_2\text{O}^{-1}$, with an average of $24.1 \text{ g C kg}^{-1} \text{ H}_2\text{O}^{-1} \pm 22.9$. For EUC ecosystem WUE_i ranged between 0.5 to 42.4 $\text{g C kg}^{-1} \text{ H}_2\text{O}^{-1}$, with an average of $19.3 \text{ g C kg}^{-1} \text{ H}_2\text{O}^{-1} \pm 7.1$.

Monthly sum of evapotranspiration in EUC ecosystem (1049) was 10% higher than SAV ecosystem (949 mm) (Table A7). The decline in LAI of 50% and reduction in soil water content may have contributed with this difference in ET between the two ecosystems. Also, was observed a strong reduction in canopy conductance, due to stomatal regulations (Table A7).

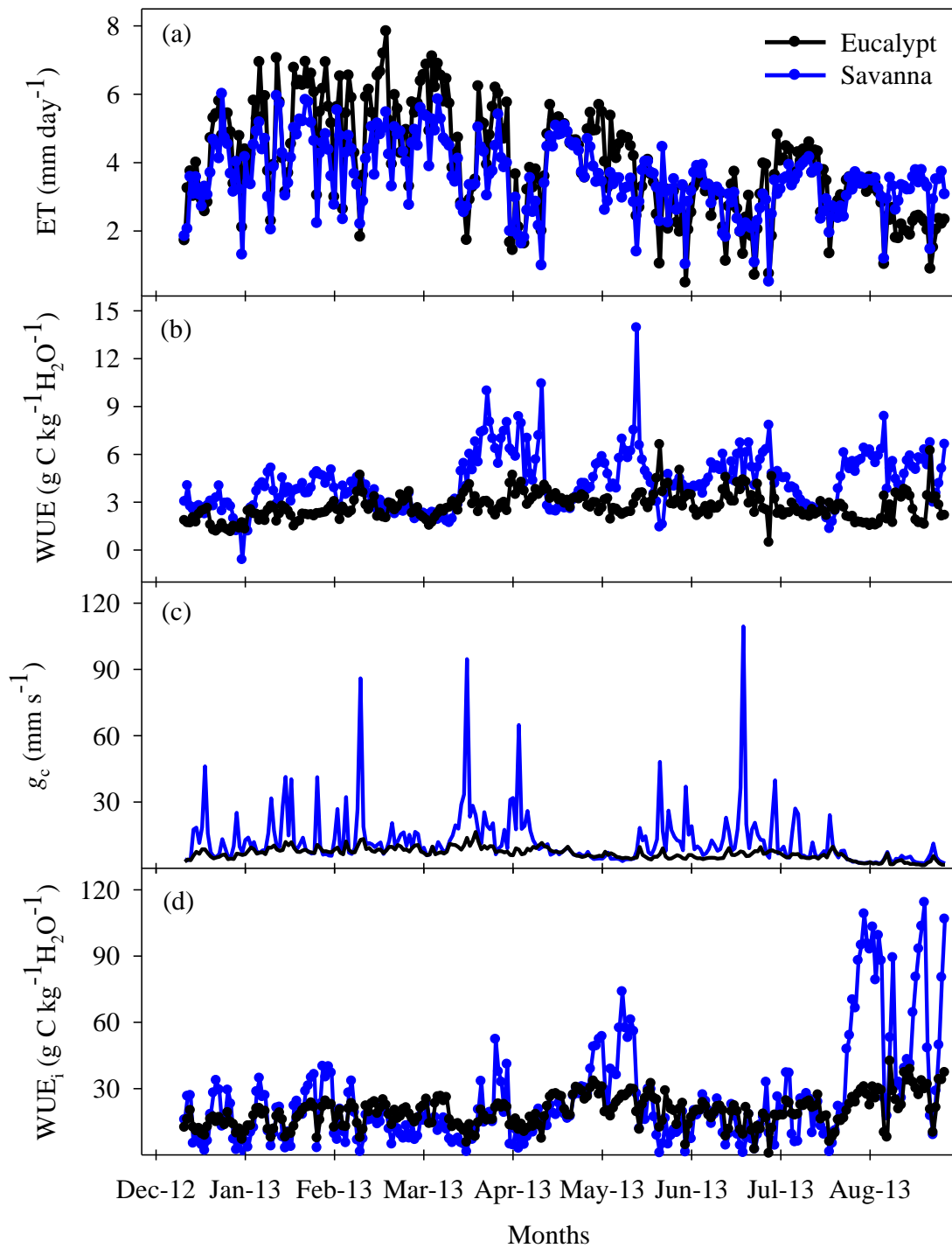


Figure 23. Daily evapotranspiration (ET, mm day^{-1}) (a), mean daily water use-efficiency (WUE, $\text{g C kg}^{-1} \text{H}_2\text{O}^{-1}$) (b), mean daily canopy conductance (g_c , mm s^{-1}) (c), and mean daily intrinsic water use-efficiency (WUE_i , $\text{g C kg}^{-1} \text{H}_2\text{O}^{-1}$) (d) at the savanna ecosystem and eucalyptus plantation in Brazilian tropics.

Canopy conductance (g_c) was plotted as a function of vapor pressure deficit (VPD) in Figure 24 for savanna and eucalypt ecosystem. During both ecosystems, g_c decrease with increasing in VPD, but more strongly at the SAV ecosystem (0 to 1.5 kPa). Savanna ecosystem are less sensitive to VPD changes (Vourlitis et al., 2001; Giambelluca et al., 2009; Cabral et al., 2015) compared to eucalypt ecosystem.

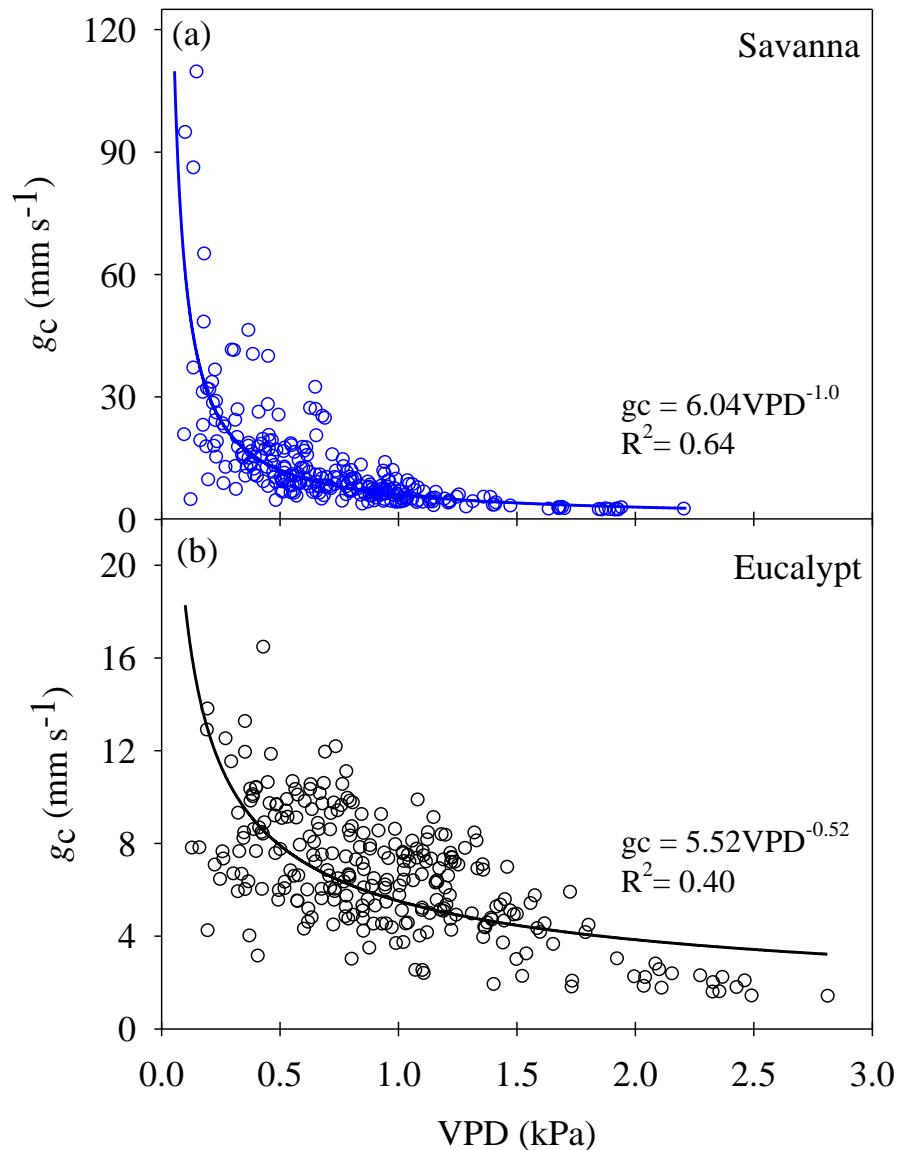


Figure 24. Scatter plot mean daily canopy conductance (g_c , mm s^{-1}) by mean daily water vapor pressure deficit (VPD, kPa) for savanna ecosystem (a) and eucalyptus plantations (b).

5. CONCLUSIONS

First study: *Eucalyptus* plantations over 9 years in Brazil

Given the importance of eucalyptus plantations in Brazil and worldwide, this study is innovating and has much to contribute in the understanding of this exchanges between the atmosphere, vegetation and the soil. The carbon balance in a spanning one full rotation cycle of *Eucalyptus* plantation in Brazilian tropics showed as a strong carbon sink, sequestering 78 t C ha⁻¹ through the 9 years of study, with a variability of 256 to 1515 g C m⁻² yr⁻¹ during 8 years and -883 g C m⁻² yr⁻¹ after harvest of trees. The main differences in a carbon fluxes was due to microclimate variability and forest management, mainly to variation in the rainfall events, fast growth of trees, and finally the harvest of trees. Compare to others eucalypt plantation, was found highest values of carbon fluxes throughout years. It is due to the better conditions to growth in Tropics compare to other climate conditions (e.g. Portugal eucalyptus stands). In general, the energy balance was dominated by LE (latent heat flux), H (sensible heat flux), and finally by soil heat flux (G) wherein was the lowest component in the energy balance. After harvest of trees the energy balance was dominated by sensible heat flux and the soil heat flux was 66% greater due to the soil cover change. Overall, the annual evapotranspiration (ET) was lower than annual rainfall, but ET was higher than rainfall in the begging of the planting. Therefore, these greater water consumption was coupled with highest resource use-efficiency, canopy conductance, and highest rates of photosynthesis (GPP = 4059 g C yr⁻¹) by trees. In conclusion, the results demonstrated that the eucalyptus plantations spanning one full rotation cycle are strong sink of carbon from the atmosphere to ecosystem coupled with high use efficiency of water, and thus can be used to improve and validate the algorithms used by remote sensing, productivity models, and ecosystem models.

Second study: Comparative of Eucalypt and Savanna ecosystems

There is growing interest in understanding the savannas areas, especially in regions with advanced stage of degradation. The major areas of savanna have been replaced by pasture and annual crops over recent decades, however recently areas with degraded pasture have been replaced by Eucalyptus plantations. The results indicate that the eucalyptus plantations in savanna biome are well adapted to the environmental conditions and have a good response to variability of climate conditions. In addition, the land-cover change and land use practices from pasture to eucalyptus plantations can help or even restore the biodiversity of savanna biome.

Unfortunately, the limited data due to failure of system do not allow calculation of the annual net ecosystem exchange (NEE) of the savanna ecosystem. Even though, the results demonstrated that savanna ecosystem is a carbon source from the ecosystem to atmospheric, releasing about 2.5 t C ha^{-1} over the study period (9 months). Therefore, these amounts of data are not enough to define if this savanna ecosystem is a carbon source entire the time, future research are need with more eddy covariance measurements to ensure about the carbon contribution in this savanna ecosystem. Otherwise, compared to fast-growth of eucalypt demonstrated a strong carbon sink from the atmospheric to ecosystem, sequestering about 11 t C ha^{-1} over the study period (9 months).

Overall, the latent heat flux (LE) dominated the energy balance at both ecosystems, followed by sensible heat flux (H) and soil heat flux (G). The carbon fluxes and evapotranspiration reduced at both ecosystems during the dry period, special for savanna ecosystem wherein a reductions of 50% of leaf area index (LAI). The evapotranspiration was higher in eucalyptus plantations (1049 mm) than in savanna ecosystem (949 mm), despite the canopy conductance (g_c) was clear higher in savanna than eucalyptus ecosystems. The high values observed in gross primary production (GPP) favored higher resource-use efficiency at savanna ecosystem compared to eucalyptus plantations, but these results still need to verified with more eddy covariance measurements.

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APPENDIX A

Table A1. Annual carbon fluxes: net ecosystem exchange (NEE, g C m⁻² yr⁻¹), net ecosystem production (NEP, t C ha⁻¹ yr⁻¹), gross primary production (GPP, g C m⁻² yr⁻¹), ecosystem respiration (Reco, g C m⁻² yr⁻¹), Reco/GPP ratio, and annual rainfall (mm yr⁻¹) for the nine year study period. The error estimates are cumulative NEE gapfilling uncertainty (u, g C m⁻² yr⁻¹).

Age	NEE (g C m ⁻² yr ⁻¹)	NEP (t C ha ⁻¹ yr ⁻¹)	GPP (g C m ⁻² yr ⁻¹)	Reco (g C m ⁻² yr ⁻¹)	GPP/ Reco	Rainfall (mm)
1	-256.3 ± 18	2.56	2312.0	2055.7	1.12	1303.1
2	-1307.8 ± 28	13.0	4059.0	2751.2	1.48	1161.2
3	-819.1 ± 66	8.19	2018.9	1195.6	1.69	986.3
4	-1479.0 ± 28	14.7	3919.6	2440.6	1.61	1063.3
5	-1153.8 ± 24	11.5	2705.0	1638.6	1.65	1356.6
6	-1316.5 ± 20	13.1	3191.2	1874.8	1.70	1287.8
7	-902.4 ± 15	9.02	2052.8	1356.3	1.51	1006.4
8	-1515.8 ± 19	15.1	3511.4	1995.6	1.76	1481.8
9	883.7 ± 10	-8.83	1248.3	2132.0	0.59	1496.8

Table A2. Monthly sum value of NEE (net ecosystem exchange, g C m⁻² month⁻¹), GPP (gross primary production, g C m⁻² month⁻¹), and Reco (ecosystem respiration, g C m⁻² month⁻¹) at eucalyptus plantations in Brazilian tropics during 9 years.

Fluxes g C m ⁻²	Age (years)	Months												Total
		Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	
NEE	1	67.8	6.3	7.2	34.6	45.9	16.3	-42.4	-80.7	-118.0	-90.4	-38.9	-64.0	-256.3
	2	-26.1	-82.3	-99.0	-96.7	-123.2	-122.1	-141.0	-112.4	-136.7	-132.6	-102.4	-133.5	-1307.8
	3	-102.0	-143.5	-127.0	-141.4	-185.5	----	----	----	----	-20.1	-53.9	-45.7	-819.1
	4	-92.3	-146.2	-101.0	-111.1	-139.4	-130.5	-142.6	-120.7	-134.4	-167.9	-81.9	-110.9	-1479.0
	5	-160.7	-83.3	-101.2	-145.1	-104.1	-71.1	-85.3	-102.0	-158.0	-99.1	-18.4	-25.5	-1153.8
	6	-30.5	-14.4	-153.0	-143.0	-173.1	-147.1	-150.4	-97.0	-151.6	-101.0	-64.7	-90.5	-1316.5
	7	-33.5	-76.8	-135.9	-119.4	-87.2	-95.9	-101.1	-68.5	-50.9	-73.7	-29.4	-30.2	-902.4
	8	-51.0	-139.4	-105.5	-107.5	-155.1	-170.2	-168.1	-156.5	-152.2	-111.7	-70.8	-127.9	-1515.8
	9	-36.7	34.9	193.6	123.9	13.8	60.7	141.9	94.1	66.0	76.6	76.6	38.3	883.7
GPP	1	148.1	199.3	177.8	153.9	130.9	150.4	190.4	205.7	254.5	242.6	181.5	277.0	2312.0
	2	243.6	380.2	446.8	405.4	416.3	346.3	354.5	356.6	368.5	213.6	201.2	325.9	4059.0
	3	315.2	338.7	328.7	327.1	380.5	----	----	----	----	50.1	101.1	177.4	2018.9
	4	373.3	469.5	344.9	380.9	417.7	341.3	340.3	244.4	266.1	310.0	162.8	268.4	3919.6
	5	174.9	294.3	301.4	333.6	243.0	222.7	229.0	214.7	262.9	191.2	111.2	126.1	2705.0
	6	156.7	186.4	359.2	385.1	400.8	386.5	337.1	238.9	262.3	172.0	138.4	167.8	3191.2
	7	59.2		242.2	260.8	338.5	256.9	198.3	151.7	131.5	157.3	123.4	132.9	2052.8
	8	235.0	359.9	352.1	291.7	324.4	349.8	310.2	306.5	314.8	195.0	179.2	292.7	3511.4
	9	280.1	342.0	29.4	70.6	214.8	81.7	7.8	12.0	12.5	21.0	54.7	121.7	1248.3
Reco	1	215.9	205.6	185.0	188.5	176.8	166.7	148.0	125.0	136.4	152.1	142.6	213.0	2055.7
	2	217.6	297.9	347.8	308.7	293.1	224.2	213.6	244.2	231.8	81.1	98.9	192.4	2751.2
	3	213.3	190.9	201.7	185.8	194.9	----	----	----	----	30.0	47.2	131.7	1195.6
	4	281.0	323.3	243.9	269.8	278.3	210.7	197.7	123.7	131.6	142.1	80.9	157.5	2440.6
	5	101.6	210.9	200.2	188.5	138.8	151.6	143.7	112.7	104.9	92.1	92.8	100.6	1638.6
	6	126.1	171.9	206.2	242.0	227.7	239.4	186.7	141.8	110.7	71.0	73.8	77.3	1874.8
	7	75.1	79.7	106.3	141.4	251.3	161.1	97.3	83.2	80.6	83.6	94.0	102.7	1356.3
	8	184.1	220.5	246.5	184.3	169.3	179.6	142.2	150.1	162.7	83.2	108.4	164.7	1995.6
	9	243.4	376.9	222.9	194.6	228.6	142.4	149.6	106.1	78.6	97.7	131.3	160.0	2132.0

Table A3. Monthly averaged energy balances for one full rotation cycle of eucalyptus plantations. (a) 1-2-3 years age; (b) 5-6-7 years age; and (c) after harvest of trees.

Period	Month	Rn (W m ⁻²)	LE/Rn	H/Rn	G/Rn	Bowen ratio (H/LE)
1	Nov	325	0.57	0.38	0.17	0.66
	Dec	349	0.67	0.27	0.10	0.40
	Jan	361	0.65	0.25	0.06	0.38
	Feb	324	0.72	0.23	0.12	0.32
	Mar	307	0.74	0.18	0.08	0.24
	Apr	254	0.83	0.13	-0.04	0.15
	May	210	0.89	0.14	-0.07	0.16
	Jun	179	0.91	0.22	-0.16	0.24
	Jul	195	0.89	0.14	-0.13	0.16
	Aug	261	0.51	0.44	-0.01	0.87
2	Sep	273	0.52	0.46	-----	0.88
	Oct	317	0.58	0.38	-----	0.65
	Nov	335	0.66	0.39	-0.03	0.59
	Dec	357	0.49	0.53	0.00	1.10
	Jan	352	0.76	0.20	0.02	0.26
	Feb	319	0.84	0.17	0.02	0.20
	Mar	305	0.79	0.28	0.01	0.36
	Apr	245	0.73	0.12	0.00	0.16
	May	212	0.75	0.06	-0.02	0.07
	Jun	181	0.72	0.10	-0.05	0.14
3	Jul	203	0.74	0.07	-0.02	0.10
	Aug	263	0.47	0.31	0.06	0.65
	Sep	277	0.44	0.33	0.08	0.75
	Oct	333	0.45	0.37	-----	0.81
	Nov	337	0.76	0.20	0.02	0.27
	Dec	287	0.58	0.30	0.02	0.52
	Jan	257	0.44	0.71	-0.05	1.60
	Feb	276	0.63	0.56	0.17	0.89
	Mar	293	0.75	0.29	0.17	0.38
	Apr	266	0.49	0.52	0.39	1.08
May	163	0.45	0.70	-0.17	1.56	
Jun	167	0.33	0.72	-0.21	2.19	
Jul	204	0.27	0.73	-0.24	2.69	
Aug	203	0.46	0.65	-0.01	1.42	
Sep	225	0.43	0.60	-----	1.41	
Oct	263	0.51	0.48	-----	0.96	

Table A4. Annual evapotranspiration (ET, mm yr⁻¹), water use-efficiency (WUE, g C kg⁻¹ H₂O⁻¹), intrinsic water use-efficiency (WUE_i, g C kg⁻¹ H₂O⁻¹), and canopy conductance (g_c , mm s⁻¹) during 9 years at a eucalyptus plantation in Brazilian tropics.

Age	Rainfall (mm)	ET (mm)	WUE g C kg ⁻¹ H ₂ O ⁻¹	WUE _i g C kg ⁻¹ H ₂ O ⁻¹	g_c mm s ⁻¹
1	1303.1	987.8	2.2 ± 5.1	21.9 ± 14.4	5.1 ± 4.1
2	1161.2	1233.5	3.8 ± 9.2	30.4 ± 21.8	6.1 ± 3.8
3	986.3	884.7	2.2 ± 1.1	21.4 ± 9.9	5.1 ± 2.6
4	1063.3	1297.5	3.2 ± 0.9	24.2 ± 11.2	6.7 ± 4.9
5	1356.6	1282.1	2.3 ± 0.8	19.6 ± 10.3	6.0 ± 4.3
6	1287.8	1297.0	2.5 ± 0.8	20.1 ± 7.3	5.7 ± 2.8
7	1006.4	968.0	2.3 ± 0.9	20.8 ± 8.0	4.3 ± 2.3
8	1481.8	1435.8	2.5 ± 0.7	20.3 ± 7.4	6.5 ± 3.1
9	1496.8	837.2	1.2 ± 0.9	10.6 ± 9.3	4.9 ± 5.2

Table A5. Monthly net ecosystem exchange (NEE, g C m⁻² month⁻¹), gross primary production (GPP, g C m⁻² month⁻¹), and ecosystem respiration (Reco, g C m⁻² month⁻¹) at the eucalyptus plantation and a savanna ecosystem in Brazilian tropics.

Months	NEE (g C m ⁻² month ⁻¹)		GPP (g C m ⁻² month ⁻¹)		Reco (g C m ⁻² month ⁻¹)	
	Eucalypt	Savanna	Eucalypt	Savanna	Eucalypt	Savanna
Dec-12	-20.5	62.0	137.0	201.2	116.5	263.2
Jan-13	-153.0	132.8	359.2	513.7	206.2	646.5
Feb-13	-143.0	-43.6	385.1	365.6	242.0	322.0
Mar-13	-173.1	-8.0	400.8	547.3	227.7	539.3
Apr-13	-147.1	17.9	386.5	433.2	239.4	451.1
May-13	-150.4	-1.3	337.1	485.6	186.7	484.4
Jun-13	-97.0	41.9	238.9	397.1	141.8	439.0
Jul-13	-151.6	27.7	262.3	360.9	110.7	388.6
Aug-13	-101.0	17.5	172.0	528.9	71.0	546.5
Totals	-1136.8	246.9	2678.9	3833.6	1542.1	4080.6

Table A6. Monthly averaged energy balances at the eucalyptus plantation and a savanna ecosystem in Brazilian tropics.

Ecosystem	Month	Rn	LE/Rn	H/Rn	G/Rn	Bowen ratio (H/LE)
Savanna	Dec	358	0.54	0.48	0.04	0.89
	Jan	349	0.65	0.33	0.02	0.51
	Feb	320	0.67	0.24	0.02	0.35
	Mar	308	0.80	0.25	0.01	0.31
	Apr	252	0.95	0.29	0.00	0.31
	May	236	0.69	0.30	0.01	0.44
	Jun	195	0.48	0.21	0.02	0.44
	Jul	224	0.73	0.45	-0.01	0.62
	Aug	261	0.68	0.41	0.05	0.60
Eucalypt	Dec	332	0.66	0.34	0.06	0.52
	Jan	349	0.79	0.20	0.04	0.26
	Feb	320	0.87	0.15	0.05	0.18
	Mar	308	0.93	0.14	0.02	0.15
	Apr	252	0.74	0.08	0.00	0.11
	May	236	0.82	0.05	-0.02	0.06
	Jun	195	0.75	0.16	-0.05	0.21
	Jul	224	0.77	0.12	-0.02	0.16
	Aug	273	0.42	0.47	0.05	1.11

Table A7. Monthly sum of evapotranspiration (ET, mm month⁻¹), water use-efficiency (WUE, g C kg⁻¹ H₂O⁻¹), intrinsic water use-efficiency (WUE_i, g C kg⁻¹ H₂O⁻¹), and canopy conductance (g_c , mm s⁻¹) at the eucalyptus ecosystem (EUC) and at the savanna ecosystem (SAV) in Brazilian tropics.

Months	ET		WUE		WUE _i		g_c	
	EUC	SAV	EUC	SAV	EUC	SAV	EUC	SAV
Dec-12	87	78	1.7 ± 0.4	2.5 ± 1.0	13.3 ± 3.4	14.2 ± 10.9	5.7 ± 1.5	11.9 ± 9.6
Jan-13	162	134	2.3 ± 0.3	3.9 ± 0.8	16.6 ± 5.1	20.5 ± 12.2	8.4 ± 1.4	14.1 ± 10.7
Feb-13	145	119	2.8 ± 0.6	3.2 ± 0.7	18.3 ± 4.2	13.4 ± 7.3	9.0 ± 1.7	16.0 ± 15.1
Mar-13	158	131	2.7 ± 0.6	4.4 ± 2.4	17.5 ± 5.7	15.9 ± 10.8	9.2 ± 2.4	17.7 ± 16.1
Apr-13	118	107	3.4 ± 0.5	4.7 ± 2.1	20.3 ± 7.0	18.4 ± 10.0	7.7 ± 1.7	13.3 ± 12.2
May-13	115	101	3.2 ± 0.9	5.0 ± 2.1	23.7 ± 5.9	30.7 ± 20.6	5.5 ± 1.3	10.0 ± 9.1
Jun-13	80	82	3.1 ± 0.7	4.9 ± 1.0	16.5 ± 5.6	14.3 ± 8.3	5.9 ± 1.5	17.2 ± 19.1
Jul-13	109	98	2.4 ± 0.6	3.8 ± 1.4	18.2 ± 6.0	22.0 ± 17.6	5.8 ± 1.5	10.0 ± 8.7
Aug-13	75	99	2.5 ± 1.1	5.4 ± 1.1	27.8 ± 8.1	65.9 ± 32.9	2.6 ± 1.2	3.8 ± 2.0