Analyses of canopy photosynthesis derived from three-dimensional model simulations of sun-induced chlorophyll fluorescence

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Faulty of Science

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Certificate of original authorship

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. This research is supported by Australian Government Research Training Program.

Signature of student: Production Note: Signature removed prior to publication.

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Publications

Wu, J., Kobayashi, H., Stark, **S.C.**, Meng, R., Guan, K., Tran, N.N., **Gao, S.**, Yang, W., Restrepo-Coupe, N., Miura, T. and Oliviera, R.C., 2018. Biological processes dominate seasonality of remotely sensed canopy greenness in an Amazon evergreen forest. *New Phytologist*, *217*(4), pp.1507-1520.

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Abbreviations

1D	1 Dimensional
3D	3 Dimensional
APAR	Absorbed Photosynthetic Active Radiation
Biome-BGC	Biome BioGeochemical Cycles
BRDF	Bidirectional Reflectance Distribution Function
Cab	total chlorophyll content
Cca	Carotenoid content
Cd	leaf dry matter
CHM	Canopy Height Model
CI_{green}	green Chlorophyll Index
Cw	leaf water thickness
DART	Discrete Anisotropic Radiative Transfer
EF-matrix	Excited Fluorescence Matrices
ESA	European Space Agency
EVI	Enhanced Vegetation Index
FLD	Fraunhofer Line Discrimination
FLiES	Forest light environmental simulator
FluorWPS	Fluorescence model with Weighted Photon Spread method
FOV	Field Of View
fPAR	Fraction of Photosynthetically Active Radiation
fqeI	fluorescence quantum efficiency for photosystem I
fqeII	fluorescence quantum efficiency for photosystem II
FVC	Fraction of Vegetation Cover
GOME-2	Global Ozone Monitoring Experiment–2
GOSAT	Greenhouse Gases Observing Satellite
GPP	Gross Primary Productivity
GPR	Gaussian Processes Regression
IA	Inner Antenna
LAI	Leaf Area Index
IGBP	International Geosphere-Biosphere Programme

LiDAR	Light Detection And Ranging
LUE	Light Use Efficiency
MODIS	MOderate resolution Imaging Spectroradiometer
N	leaf structure
NEE	Net Ecosystem Exchange
NDVI	Normalized Difference Vegetation Index
NPQ	NonPhotochemical Quenching
OA	Outer Antenna
OCO-2	Orbiting Carbon Observatory-2
PAR	Photosynthetic Active Radiation
PRI	Photochemical Reflectance Index
PPFD	Photosynthetic Photon Flux Density
PSI	Photosystem I
PSII	Photosystem II
RBF	Radial-Basis Function
RMSE	Root Mean Square Error
RTM	Radiation Transfer Model
SAA	Solar Azimuth Angle
SCIAMACHY	SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY
SCOPE	Soil Canopy Observation, Photochemistry and Energy fluxes
SFM	Spectral Fitting Method
SI	Scenario I
SIF	Sun-Induced chlorophyll Fluorescence
SII	Scenario II
SWC	Soil Water Content
SZA	Solar Zenith Angle
Ta	air Temperature
TOC	Top Of Canopy
TROPOMI	TROPOspheric Monitoring Instrument
UAV	Unmanned Aerial Vehicles
VAA	View Azimuth Angle
VI	Vegetation Indices

Vmax	Maximum Carboxylation Velocity
VPD	Vapour Pressure Deficit
VPM	Vegetation Photosynthesis Models
VZA	View Zenith Angle

Abstract

Recently, measurements of sun-induced chlorophyll fluorescence (SIF) has become a new approach to estimate vegetation photosynthetic activity and detect vegetation stress. However, the environmental factors controlling SIF largely remain unknown for different vegetation biome types. In addition, SIF measured at the top of canopy (TOC) is confounded by interactions between solar radiation and vertical canopy structures. Hence, development of three-dimensional (3-D) radiative transfer models, capable of simulating SIF, would be of immense benefit to test and verify various hypothesises.

The goal of this thesis is to develop a new 3-D SIF model and apply it to assess the relationship between SIF and plant photosynthetic activity across different spatial and temporal scales. Specifically, I (1) developed a new SIF module for FLiES (Forest Light Environmental Simulator) model (FLiES-SIF) and validated it with SIF observations at the seasonal scale; (2) partitioned SIF signals to overstory and understory layers by using FLiES-SIF, and then analysed the impact of solar radiation and canopy structure on understory SIF; (3) normalized the OCO-2 SIF dataset at nadir, hotspot and darkspot viewing directions by using the FLiES model, and assessed the relationship between SIF and GPP; and (4) identified that SIF observed at the top of canopy was strongly influenced by understory reflectance and canopy structure.

Results showed (1) the TOC SIF simulated by FLiES-SIF was closely correlated with SIF observations at a forest test site, and its performance was better than a 1-D model (Soil Canopy Observation, Photochemistry and Energy fluxes, SCOPE) and 3-D model (Discrete anisotropic radiative Transfer, DART); (2) the SIF emitted from understory contributed more than 51 % to the total SIF in the wet season of a tropical savanna site, however, it only accounted for less than 10% of total SIF in an evergreen forest site; (3) SIF was most correlated with GPP in the hotspot direction, and the normalised SIF yield could better explain the variations of light use efficiency (LUE); (4) compared to canopy structure and leaf properties, the understory reflectance was the primary factor influencing the observed SIF at the top of the canopy.

This thesis highlights the advantage of FLiES-SIF in capturing vegetation photosynthetic activities of ecosystems with complex canopy structures. This will significantly improve

our understanding of vegetation responses to climate change, and this model can be implement for numerous related purposes.