**Enhancing Functional-Structural Plant Models through Comprehensive Data Collection and Climate Scenario Analysis: A Case Study on Oil Palm Plants**

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# Abstract

Functional-structural plant models (FSPM) aim to replicate the intricate ecophysiological and developmental responses of plants to their surroundings environment. These models can be valuable for studying plant behavior in a changing climate but rely heavily on detailed structural and ecophysiological data. Limited databases hinder FSPM assessment due to the high cost and time required for data collection, including plant geometry, topology, and ecophysiological measurements. This scarcity often results in the omission of comprehensive FSPM evaluations.

A new dataset is proposed for FSPM evaluation at leaf to plant scale. Oil palm plants (*Elaeis guinnensis*) were sequentially placed in a growth chamber, where continuous measurements of H2O fluxes, CO2 fluxes, and leaf temperature were taken, alongside controlled air temperature, vapor pressure deficit, photosynthetically active radiation, and air CO2 concentration. This setup allowed for the investigation of the impact of climate variables on plant assimilation and transpiration through eight daily climate scenarios replicated on four plants. The dataset also includes data for model parameterization, such as detailed reconstructions of the 3D plant structure from terrestrial LiDAR point clouds and measurements of photosynthesis and stomatal conductance using leaf-scale response curves from a gas analyzer (including A/Ci, A/PPFD, and Gs/VPD response curves). The three-dimensional reconstructions of the plants and the growth chamber were utilized to create a digital twin of the experiment.

This database stands out for its comprehensive and complementary observations, enabling the testing of hypotheses on the spatial integration of physiological processes and the accuracy required in representing plants to capture the relationship between structure and function in FSPM.

Keywords: response curve; FSPM; temperature; radiation; VPD; CO2

# Introduction

Functional-structural plant models (FSPM) aim at reproducing the complexity of the ecophysiological and developmental responses of plants to their environment. Such models can be particularly useful to understand and explore plant behaviour in a changing climate, but depend on intensive collection of structural and ecophysiological data. Since errors can rise from different sources such as model implementation, calibration, and coupling, model evaluation can be a major difficulty. Furthermore, some sub-models simulate processes at fine scale (e.g. leaf scale) but the output of interest is an integration at a larger scale (i.e. plant or plot scale), which can also add errors that are difficult to assess when evaluation is only made at the finer scale. Lastly, very few databases are available for the assessment of FSPM because they require expensive and time-consuming measurements, including plant geometry and sometimes topology, ecophysiological data such as response curves (e.g. A-Ci), and whole-plant measurements to control for the error coming from the upscaling. Consequently, the assessment of an FSPM as a whole is usually omitted because of the lack of such data. However, it's crucial to thoroughly evaluate a model's ability to accurately replicate observed processes before applying it to avoid drawing incorrect conclusions.

Biophysical models like ARCHIMED (Dauzat & Eroy, 1997) simulate processes such as light interception, photosynthesis, transpiration and temperature at the leaf level under various environmental conditions. These models utilize leaf-scale measurements to parameterize different sub-models, enabling the upscaling of processes to the plant or plot level. Applications of these models range from simulating hard-to-measure variables (e.g., water and energy balance) to predicting system behavior under unfamiliar conditions (e.g., assessing climate change impacts) or even guiding trait selection for plant ideotyping. Evaluating a model becomes more challenging when numerous interconnected processes are simulated, as is often the case with biophysical processes in natural systems.

One approach to address this challenge is to compare model outputs with observations. However, observations are typically not conducted under highly controlled conditions with precise measurements, leading to additional unexplained sources of error. Schymanski and Or (2017)attempted to tackle the need for precise measurements in model evaluation, but their data is only relevant at the scale of an individual artificial leaf.

The proposed experiment aims to establish a database for evaluating a 3D biophysical model, by comparing measured CO2 fluxes, H2O fluxes, and leaf temperature with their simulated counterparts. This database provides all the elements needed to construct a digital twin o the experiment, such as growth chamber conditions, the 3D architecture of plants over time, and leaf-scale response curves obtained from a gas analyzer to calibrate photosynthesis and stomatal conductance models. The raw data and scripts used to generate the final database are detailed and accessible on the following GitHub repository: <https://github.com/PalmStudio/Biophysics_database_palm/tree/main>.

# Material & Method

## Plant material and growing conditions

Four oil palm plants (*Elaeis guineensis Jacq.*) were studied, which included two genetic origin: Deli x Lame crossing (P1, P2 & P4) and a Deli x Yamgambi crossing (P3). The plants were sown on May 11th, 2020, and were cultivated in a glasshouse (Abiophen platform, CIRAD, Montpellier, France) under the following conditions: a temperature of approximately 26°C the day, 21°C the night, a relative humidity of 70%, a photosynthetically active radiation (PAR) of 600 µmol m-2 s-1, and an air CO2 concentration ([CO2]) of around 400ppm. To prevent water stress, the plants were irrigated every two to three days. On February 25th, 2021, the plants were transferred to the Ecotron (CNRS, Montpellier, France) and placed in a growth chambers wiht higly controlled climate, called microcosms. Two microcosms where used during 2 months to carry out the experiment. The two microcosms are 114cm (Width) x 113cm (Depth) x 152cm (Height) chambers with a radiation and climate control system that can precisely control the temperature, humidity, and CO2 concentration. The first microcosm was used to store three plants (storage microcosm), and the second one was used to measure the fluxes of a single plant in response to various climate conditions (see section Climate scenarios). Each plant took turns in the flux microcosm for three to five days (Figure 1).



Figure 1: Plant succession and climate scenarios in the flux microcosm. Grey cells indicate dates on which the plant is in the storage microcosm. Points indicate date of leaf gas exchange (black crosses) and dates of 3D reconstruction of plants.

The scenarios with potential negative impacts on plant functionning du to extreme high temperature were performed the last days of measurements for each plant. Some repetitions of a scenario were performed to estimate changes in plant functionning over time. In the storage microcosm, the climate conditions were fixed to the reference scenario (400ppm), and each plant was irrigated every 6 hours using an irrigation system.

At the end of the experiment, additional measurements were conducted to assess the correlations between leaf-level gas exchanges and plant-level gas exchanges. The aim was to investigate whether leaf gas exchange is influenced by overall plant conditions, particularly focusing on the light environment. The tests involved placing a plant in the flux chamber, with one leaf attached to the Walz leaf gas analyzer. The conditions within the Walz head remained constant in terms of temperature, [CO2] and relative humidity, while the light was either at saturation (1500 μmolphoton m-2 s-1; WalzClose test) or following the ambient conditions by excluding the light component from the head (WalzOpen test). During both tests, the climate conditions within the flux chamber followed the reference scenario (400ppm), but the light ranged from darkness to peak photosynthetically active radiation (PAR) levels (Figure S1). These tests were carried out on two plants (Figure 1).

The amount of water added during irrigation was adjusted over time to maintain non-limiting soil water availability throughout the experiment. In the flux microcosm, an irrigation system was also implemented to provide water every 6 hours, and the top of the pot was sealed with a non-emitting CO2 plastic bag to isolate the soil and roots, allowing only water and carbon fluxes from the aerial part of the plant to be measured (Figure 2).



Figure 2: Oil palm plant in the flux microcosm. The pot was sealed to prevent measuring soil fluxes. A scale was positioned under the pot to measure plant transpiration using gravimetry. Sensors for photosynthetically active radiation, temperature, and relative humidity were installed in the chamber to regulate the environmental conditions. The head of the leaf gas exchange analyzer was positioned in the chamber to conduct either CO2 response curves (storage microcosm) or to follow leaf assimilation during specific scenarios (WalzOpen or WalzClose tests) in the flux chamber.

## Climate scenarios

The chambers allowed for precise control of radiation in the visible spectrum with four LED lamps, as well as the climatic conditions, including temperature (5-50±0.5°C), relative humidity (20-90±3%), and CO2 concentration (10-2000ppm). The climate conditions in the microcosm were defined based on the average daily variation observed at a weather station in Pekanbaru, Indonesia, where the conditions are known to be optimal for oil palm cultivation. This base condition was then modified by adjusting the CO2 concentration, radiation, temperature, and relative humidity. The resulting climate scenarios were as follows: (Figure 3):

* 400ppm: the base condition
* 600ppm: +50% [CO2]
* 800ppm: + 100% [CO2]
* Cloudy: the same as base condition but with the PAR values based on the most cloudy day of our database from the weather station. The dynamic of the PAR is kept as in the base condition though. The maximum PPFD was 130 µmol m² s⁻¹ at 51cm from the lamps, compared to 300 in the reference scenario.
* Cold: -30% °C
* Hot: +30% °C
* DryCold: -30% relative humidity and -30% °C
* DryHot: -30% relative humidity and +30% °C



Figure 3: Monitoring of radiation, temperature, and relative humidity over time for the eight climate scenarios. Each transparent line represents a day of measurement, while the bold line signifies the median value across all days. Measurement of photosynthetically active radiation was conducted at the center height of the chamber. The reference scenario is the ‘400ppm’ scenario.

## CO2 and H2O fluxes at the plant level

CO2 fluxes were measured using a flow-through open system (Picarro G2101-I CO2 analyzer) connected to the chamber. This system recorded the input [CO2] in the chamber for 5 minutes, followed by measuring the output [CO2] for another 5 minutes. The difference between these two [CO2] values allowed for the calculation of CO2 fluxes resulting from plant photosynthesis or respiration within the chamber's air volume.

Transpiration was calculated through gravimetry using a precision scale connected to a datalogger, enabling the monitoring of plant weight over time. Any variations in the weight of the potted plant were considered to be a result of water loss through transpiration, as the pot was sealed with plastic film. Irrigation phases were identified by significant increases in pot weight, and the data was processed accordingly to accurately differentiate between transpiration and irrigation. Transpiration was calculated using two distinct methods. The first method involved measuring the weight difference, where transpiration was determined by the variance in weight between the beginning and end of the measurement period. The second method, known as the regression method, calculated transpiration by analyzing the slope of the linear regression of weight over time for all data points within the specified time frame.

## Leaf gas exchange: calibrating photosynthesis and stomatal conductance

The leaf-level response to changing conditions was assessed using a Walz GFS-3000 portable chamber. Initially, half of the plant leaves were measured in the laboratory during a pre-experiment, alongside SPAD measurements. These measurements aimed to determine the impact of leaf nitrogen content (as indicated by the SPAD value) on the photosynthetic parameters of the leaf. The hypothesis suggested that leaf nitrogen content is associated with leaf age and/or position (where leaf position, or rank, corresponds to its age).

Typically, very young leaves are believed to have a lower photosynthetic capacity, while more mature leaves exhibit higher photosynthetic capacity, which then decreases with age due to nutrient remobilization. This dataset was utilized to establish a relationship between SPAD values and their effects on photosynthetic parameters.

Before subjecting the plants to various climatic sequences in the flux microcosm (see Figure 1), one leaf per plant was measured in the storage microcosm. The aim was to assess the plant's photosynthetic capacity immediately before implementing the sequences, aiming to calibrate models as realistically as possible while considering factors such as plant age. This measurement also served to explore the necessity of systematic measurements for simulating a plant and to determine if different scenarios impacted the plant's photosynthetic capacity over time. For instance, it helped evaluate whether challenging conditions like a hot and dry scenario imposed significant stress on the plant. The measurements involved conducting a response curve of carbon assimilation in relation to the increasing internal concentration of CO2 (A-Ci curves), followed by another response curve of carbon assimilation to decreasing photosyntetic photon flux density (A-PPFD curves) and a last response curve of carbon assimilation and stomatal conductance to increasing vapor pressure deficit (VPD). To elevate the VPD, the relative humidity within the chamber was decreased while maintaining a constant temperature. These curves were consistently carried out on the same leaf rank, specifically selected as the penultimate fully expanded leaf. Additionally, during each day of measuring response curves, SPAD values were recorded for all leaves of the plant.

In the database, A-Ci curves were used to fit the Farquahr-van Caemmerer-Berry (FvCB) model for C3 photosynthesis (Farquhar et al., 1980) and estimate the parameters *VCmax*, *Jmax*, *Rd* and *TPU*. Response curves to VPD were used to estimate the parameters of the stomatal conductance model of Medlyn (Medlyn et al., 2011), i.e *g0* and *g1.*

## Leaf temperature

Leaf temperature was measured with a a FLIR Vue™ Pro R thermal camera that took one image every second. The camera was placed on the farthest top left corner of the chamber, pointing down towards the center of the chamber to ensure the best visibility of the plant leaves. The images were collected from March 2nd to May 3rd and processed to select parts of the images corresponding to identifiable leaves. Masks were computed in the region of the leaf that was visible and did not move due to the wind inside the chamber or any manipulation throughout the day of measurement (Figure 4). Subsequently, leaf temperatures were calculated, factoring in the influence of air temperature and relative humidity within the chamber. The mean, the maximum, the minimul and the standard deviation of the pixel temperatures within the masks were then calculated for each time step of the chamber measurements.

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Figure 4: A) Masks of leaf area for estimating leaf temperature. The mask is located at the center of the leaf to avoid capturing image pixels that may not consistently represent the leaf due to internal chamber wind. The colors represent the different masks of the monitored leaves. B) Temperatures of leaves and the air temperature (black points) over a day.

## Plants architecture

The LiDAR scans of the four plants were conducted every week throughout the entire period of flux measurements. At least three viewpoints were utilized to ensure accurate registration of the entire plant and minimize issues caused by occlusions. At the end of the experiment, the leaves were removed one by one from the plant and scanned individually. This individual leaf scanning was carried out to enable a detailed reconstruction of the leaves, as achieving this level of detail was not feasible with the full plant 3D point cloud due to leaf overlap at the plant's center. Plant reconstructions were carried out manually in Blender (Blender Development Team, 2022), utilizing plane meshes to shape polygons on leaf point clouds (poly build tool with automatic merging of vertices on points, as shown in Figure 5A). The most recent LiDAR scans were initially reconstructed to isolate leaves and facilitate the entire plant reconstruction process. Subsequently, the point clouds from the previous date were reconstructed using the subsequent date, updating leaf geometry and position within the plant by aligning them with the point cloud (Figure 5B). Each time a plant was placed in the microcosm to undergo a climate scenario sequence, we selected the LiDAR point cloud that best represented these dates for reconstruction. Due to the slow development of the oil palm, we opted to restrict the number of reconstructions due to the extensive time required for each reconstruction. Ultimately, four dates were chosen to capture the evolution of the plant architecture for each plant (see Figure 1).



Figure 5: 3D reconstruction from LiDAR point clouds. A) Building plane meshes on point cloud with the poly build tool of blender. B) Full reconstruction of the 3D mock up from points cloud.

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