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Long-term monitoring of tropical oil palm ecosystem fluxes: A comparative study of two ENSO events in Jambi, Indonesia

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Abstract

The conversion of tropical landscapes into monoculture plantations like oil palm (*Elaeis guineensis*) has fundamentally altered regional carbon and water cycle dynamics. Understanding how oil palm plantations respond to the El Niño-Southern Oscillation (ENSO) is critical for predicting their long-term sustainability. This study presents a comparative assessment of the biophysical and biogeochemical responses of a mature oil palm plantation (FLUXNET site ID-JOP) in the lowlands of Sumatra, Indonesia, from 2014 until 2025. To evaluate ecosystem-scale carbon and water dynamics, high frequency (10 Hz) eddy covariance measurements were obtained from a 22 m tower using a Metek USA-1 sonic anemometer and a LI-7500A open-path infrared gas analyser.

A data processing chain to ensure high-quality meteorological and eddy covariance flux data has been developed. Further for data continuity, meteorological and flux variables have been gap-filled by using a XGBoost machine learning approach and integrating ERA5-Land climate reanalysis data; any remaining long gaps were subsequently filled using a Random Forest model. We quantified Net Ecosystem Exchange, Gross Primary Productivity, Ecosystem Respiration and ecosystem functional properties including Evaporative fraction, Water-use efficiency, and surface conductance. To identify drivers and their contributions, XGBoost machine learning models in combination with SHapley Additive exPlanations (SHAP) analyses were applied.

Previous studies indicate that the 2015 peak was uniquely characterised by a bimodal driver distribution, an initial phase of radiation-driven uptake was superseded by a severe radiative deficit caused by aerosol-induced smoke haze originating from wildfires during the ENSO drought. In contrast, we hypothesise that the less severe 2023-24 event will exhibit a unimodal distribution, where NEE is primarily regulated by thermodynamic constraints. During such El Niño phases, atmospheric vapour pressure deficits typically increase, inducing a reduction in canopy stomatal conductance and other ecophysiological functions to balance carbon gain against water consumption. By comparing the 2015 and 2023 El Niño events, this research characterises how ENSO intensity regulate carbon sequestration.

Keywords: Carbon fluxes, eddy covariance, enso variability, Indonesia, land–atmosphere interactions, tropical agroecosystems

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