

Zhong et al. “Elevated shortwave radiation enhances the limitation of atmospheric dryness on carbon sequestration across European forests”

General comments:

This manuscript investigates the joint effects of shortwave solar irradiance (SW) and vapor pressure deficit (VPD) on net ecosystem exchange (NEE) across 23 European ICOS eddy-covariance sites. I recognize the timeliness and importance of evaluating compound atmospheric drought alongside solar-brightening feedbacks. However, mathematical artifacts, ecophysiological implausible response thresholds, flawed machine-learning validation, and unjustified cross-scale extrapolations fundamentally weaken the manuscript’s central conclusions. In particular, the reported increase in VPD sensitivity under high radiation does not establish a novel physiological mechanism. Instead, it largely reflects well-documented emergent behavior in coupled photosynthesis–stomatal conductance formulations, the mathematical endogeneity inherent in the Penman–Monteith inversion, and canopy radiative-heating effects. The work requires substantial reanalysis and extensive structural revisions before it is suitable for publication.

Major Scientific Concerns:

Methodological Artifacts in Machine Learning, Threshold Detection, and Path Modeling

The empirical thresholds ($\tau_1 = 3.90$ hPa, $\tau_2 = 20.84$ hPa) and the attribution models have serious analytical and ecophysiological limitations:

The XGBoost framework introduces substantial temporal data leakage by randomly partitioning half-hourly records into 80% training and 20% validation subsets. Because eddy-covariance observations show pronounced diurnal periodicity and temporal autocorrelation, the elevated validation scores ($R^2 = 0.72$ for NEE, 0.78 for GPP_{DT}) likely reflect interpolation between chronologically adjacent records rather than genuine out-of-sample predictive skill. The authors should evaluate model generalization using block cross-validation (e.g., leave-one-year-out or spatial leave-one-site-out).

Fitting continuous piecewise regressions to TreeSHAP surrogate values instead of direct observations identifies the algorithmic splitting boundaries of gradient-boosted trees, not biological tipping points. In addition, the unrealistically narrow 95% bootstrap confidence interval reported for τ_1 (3.87–3.93 hPa; ± 0.03 hPa) results from fitting regressions to pre-binned medians from hundreds of thousands of pooled observations. This approach collapses observational flux variance and ignores the spatio-temporal clustering of eddy-covariance data.

Ecophysiological, an inflection threshold of 3.90 hPa (0.39 kPa) is an implausible trigger for stomatal down-regulation in temperate and Mediterranean forests. In these forests, stomata maintain an operational conductance plateau under low evaporative demand and typically down-regulate only when VPD exceeds 0.8–1.5 kPa. Under near-saturated air (< 0.4 kPa), latent heat fluxes approach instrument detection limits, and relative measurement errors peak. Indeed, Sections 3.3 and 3.4 expose the fragility of this threshold: the authors contradict their own breakpoint by discarding all data below 5.0 hPa to exclude conditions “without atmospheric dryness stress.”

Finally, the SW binning strategy used in the covariance-based structural equation modeling (CB-SEM) introduces severe discretization artifacts. Stratifying observations into narrow 50 W m^{-2} bands suppresses radiation variance, which mathematically drives the direct path

coefficient (SW $\Rightarrow$ NEE) toward zero (from -0.23 to -0.02). Because elevated SW bins coincide with midday conditions characterized by peak temperatures and evaporative demand, this stratification systematically confounds the observed increase in the VPD $\Rightarrow$ NEE path coefficient (from -0.01 to 0.64).

Mathematical Endogeneity and Conductance Scaling

The reported sensitivity of ecosystem conductance (G_s) to VPD under high irradiance is largely a mathematical and scaling artifact:

First, inverting the Penman–Monteith equation algebraically embeds VPD in the denominator ($G_s \propto LE/VPD$). Because latent heat flux (LE) is substantially higher under high solar irradiance, plotting G_s against VPD mechanically dictates a steeper hyperbolic decline ($y \propto 1/x$). The authors further hardcode this algebraic dependency by fitting the empirical function $G_s = a / (1 + b \cdot VPD)$. Asserting that “this pattern is also consistent with theoretical expectations from the Penman–Monteith framework (Eq. 2), which predicts stronger stomatal regulation” (Section 3.4, L. 366–368) conflates a physical transport inversion with an active ecophysiological feedback.

Second, analyzing absolute departures ($\Delta G_s = G_s - \bar{G}_{s,bin}$) rather than proportional adjustments conflates intrinsic sensitivity with baseline conductance. Because high irradiance stimulates baseline stomatal opening ($g_{s,ref}$) to facilitate carbon assimilation, the absolute decline in conductance per unit VPD is naturally magnified as established by classic stomatal scaling theory (Oren et al., 1999: $-dg_s/d \ln D \approx m \cdot g_{s,ref}$) and reaffirmed in recent syntheses (e.g., Grossiord et al., 2020; Novick et al., 2016). Once normalized to relative sensitivity ($-\partial \ln G_s / \partial \ln VPD$), stomatal responsiveness often proves largely invariant across light regimes.

Oren, R., Sperry, J. S., Katul, G. et al. (1999). Survey and synthesis of stomatal responses to vapor pressure deficit. *Plant, Cell & Environment*, 22(12), 1515–1526.

Grossiord, C., Buckley, T.N., Cernusak, L.A. et al. (2020). Plant responses to rising vapor pressure deficit. *New Phytologist*, 226, 1550–1566.

Novick, K., Ficklin, D., Stoy, P. et al. (2016). The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. *Nature Climate Change*, 6, 1023–1027.

Biophysical Disconnects: Microclimatic Heating, Respiration, and Gas Exchange

Although the manuscript mentions leaf-to-air temperature differences in the Introduction, its analytical framework treats the forest canopy as an isothermal box, conflating leaf microclimate and respiratory kinetics with stomatal regulation:

Stomata respond directly to the VPD at the leaf surface within the canopy boundary layer ($D_{leaf} = e_s(T_{leaf}) - e_a$), not to ambient atmospheric dryness measured tens of meters above the canopy (D_{air}). Under high irradiance (SW > 500 W m⁻²), sensible heat loading raises leaf temperatures several degrees above ambient air ($T_{leaf} > T_{air}$). Because saturation vapor pressure (e_s) increases exponentially with temperature via the Clausius–Clapeyron relationship, sunlit canopies experience a substantially greater true evaporative demand than tower instruments record. Without quantifying canopy decoupling (Ω) or estimating D_{leaf} , the reported “amplification” cannot be isolated as stomatal regulation rather than microclimatic thermodynamic heating.

Although the authors examine partitioned GPP in Section 3.1 (Fig. 4), standard flux-partitioning algorithms (e.g., Reichstein et al. 2005; Lasslop et al. 2010) rely on prescribed temperature-respiration equations (Q_{10} temperature coefficient and Lloyd–Taylor function)

and arbitrary VPD thresholds (e.g., 10 hPa). Thus, training machine-learning models on flux-partitioned GPP risks teaching them the partitioning algorithms' assumptions rather than unconstrained biological relationships.

In the CB-SEM (Fig. 6 and Section 4.1), the direct path coefficient for $T_A \Rightarrow \text{NEE}$ changes from +0.18 at low SW to -0.44 at high SW. The authors interpret this as high temperatures stimulating net carbon uptake (negative NEE) more than respiration under strong light. However, this claim directly contradicts basic plant thermal optics, midday enzymatic downregulation, and the exponential acceleration of respiration ($R_{\text{eco}} = R_a + R_h$). This counterintuitive shift strongly suggests severe collinearity suppression among SW, T_A , and VPD in the SEM, rather than a genuine physiological mechanism.

Internal Inconsistency and Unsubstantiated ESM Deficiencies

In the Conclusion (Section 5), the authors caution that if Earth system models (ESMs) fail to capture the amplifying effect of radiation on atmospheric dryness, they risk underestimating climate impacts on carbon uptake. However, this speculation directly contradicts the authors' discussion in Section 4.1, which notes that this interaction is consistent with standard leaf-level formulations, including the Ball–Berry (Ball et al., 1987) and Medlyn (Medlyn et al., 2011) models.

Modern land-surface schemes (e.g., CLM, ORCHIDEE, JULES, and JSBACH) already couple stomatal conductance directly to radiation-driven assimilation through these formulations. Because marginal stomatal sensitivity to vapor pressure deficit ($\partial g_s / \partial D$) naturally scales with assimilation, a greater absolute reduction in conductance under high shortwave radiation emerges from the existing model physics. The authors cannot invoke Ball–Berry/Medlyn schemes to explain their empirical mechanism in Section 4.1 while also hypothesizing an ESM deficiency in Section 5 without benchmarking their observations against actual land-surface model outputs. The speculative claims in Section 5 about model failures and BECCS vulnerabilities should either be supported by explicit model evaluations or removed.

Taxonomic Aggregation, Biome Bias, and Root Hydrology

The 23 sites span contrasting hydraulic architectures, from isohydric conifers (e.g., *Picea abies*), which reduce stomatal conductance early to preserve xylem safety margins, to anisohydric broadleaves (e.g., *Quercus robur*), which tolerate severe xylem tension to sustain assimilation. Although the authors evaluate DBF and ENF subsets in the Supplementary Information, reporting near-identical inflection thresholds ($\tau_1 = 3.80$ hPa for DBF vs. 4.53 hPa for ENF) still aggregates substantial evolutionary and functional variation into coarse categories. Furthermore, pooling all 23 sites (13 ENF, 6 DBF, 2 mixed forests, 1 EBF, and 1 DNF) into primary continental thresholds (τ_1, τ_2) obscures these hydraulic distinctions.

In addition to functional differences, the site network is strongly dominated by evergreen needleleaf forests (13 of 23 sites), with nearly half located in high-latitude boreal Fennoscandia. This composition may skew aggregate European patterns toward cold, energy-limited systems with narrow hydraulic safety margins, limiting how well the findings generalize to temperate deciduous forests and water-limited Mediterranean forest regimes.

Finally, relying solely on uncalibrated surface-layer soil water content overlooks deep root-zone reserves, water stored in fractured bedrock, and access to capillary groundwater, all of which are common in mature European stands. When trees can access subsoil water, high atmospheric VPD can sustain elevated transpiration without triggering stomatal closure,

provided whole-plant hydraulic transport capacity (K_{plant}) is not exceeded. Attributing the observed flux dynamics to atmospheric dryness without accounting for root-zone moisture buffering therefore leaves the isolation of atmospheric drought incomplete.

Unjustified Narrative Extrapolation and Acclimation Gaps

In Section 4.3 and the Conclusion, the authors extrapolate sub-daily (30-minute) flux sensitivities across a 5-year window (2019–2024) to multi-decadal climate projections (mid-21st century brightening) and the feasibility of continental BECCS. While Section 4.3 briefly acknowledges temporal scale dependency, the manuscript’s broader implications directly contradict this caveat.

Most notably, the authors justify using the 2019–2024 period in Section 2.1 to “minimize potential confounding effects from long-term physiological adjustments of photosynthesis and respiration, such as thermal acclimation”. It is logically inconsistent to intentionally isolate instantaneous responses by excluding acclimation and then use those same responses to infer multi-decadal carbon-sink vulnerability, where structural and physiological acclimation, such as shifts in Huber values, redistribution of rooting depth, and thermal acclimation of $V_{c \text{ max}25}$ and $J_{\text{max}25}$, dominate ecosystem trajectories. The speculative statements regarding mid-century forest sinks and BECCS in Sections 4.3 and 5 should either be removed or heavily qualified.

Specific/minor comments:

Introduction

- In Paragraph 3, please clarify whether the cited study by Kašpar et al. (2024) addresses stem radial increment or growth, or instantaneous carbon exchange. This distinction between wood formation kinetics and half-hourly canopy gas exchange is essential for physiological context.
- In Paragraph 4, it would be better to link the identified knowledge gaps directly to the study’s explicit objectives and specific research questions.

Data and Methods

- In Section 2.1, pairing 1-km, 4-day MODIS LAI products with half-hourly tower fluxes creates a pronounced spatial and temporal mismatch with the dynamic eddy-covariance footprint. The authors should clarify how they addressed this discrepancy or assess its influence on the observed relationships.
- In Section 2.2, the XGBoost architecture lacks sufficient hyperparameter optimization. Fixing the model at 100 boosting rounds without reporting cross-validated tuning of key parameters, particularly maximum tree depth, learning rate, and regularization (λ, α), creates a substantial risk of depth-dependent overfitting.
- The exclusion of data with $\text{VPD} \leq 5.0$ hPa (Section 3.3, L. 339–341) is introduced abruptly in the Results rather than defined in the path analysis methodology in Section 2.4. Moreover, discarding observations below 5.0 hPa does not adequately resolve the structural conflict between the demonstrated piecewise nonlinearities and the linear CB-SEM assumptions. Please formally document this screening rule in Section 2.4 and assess whether linear path analysis is robust under non-normal, collinear midday conditions.
- In Section 2.5, the inversion of the Penman–Monteith equation assumes complete surface energy balance closure ($R_n - G = H + \text{LE}$). Because eddy-covariance measurements routinely show a 10% to 30% closure gap, inverted canopy conductances may be

systematically biased unless an energy balance adjustment is applied or an uncertainty bound is included.

Results

- Throughout Section 3, the text often describes VPD effects as “shifting from negative to positive” or “strengthening” based solely on SHAP coordinate values. Because SHAP metrics quantify additive model deviations relative to a base value ($E[f(x)]$) conditioned on training sample distributions, please revise the phrasing to clearly distinguish statistical feature contributions from physical flux dynamics.
- The reporting of GPP thresholds is ambiguous and internally contradictory. Specifically, the manuscript states that “the first threshold from the nighttime partitioning method has corresponding τ_2 values of 20.38 hPa and 18.76 hPa.” It is unclear whether these values correspond to τ_1 , τ_2 , or distinct thresholds derived from the daytime and nighttime partitioning methods. Please clarify the parameter definitions and ensure consistent notation across both partitioning schemes.
- In Section 3.3 and Figure 6, the abrupt reversal of the $T_A \Rightarrow \text{NEE}$ path coefficient from +0.18 to -0.44 should be explicitly tested for collinearity suppression rather than interpreted as biological stimulation of carbon uptake.

Discussion

- In Section 4.3, although the discussion evaluates atmospheric dryness, it does not adequately address multi-year soil moisture drought legacies. Please explain how cumulative depletion in the root zone and subsoil, documented during recurrent European compound drought events, may compound or decouple the observed sensitivities to solar radiation and atmospheric evaporative demand.

Abstract and Conclusions

- The Abstract and Conclusion might need to be revised based on the Major Scientific Concerns.