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Ensemble Machine Learning and Derivative Spectroscopy for Robust Estimation of Plant Physiological Traits in Precision Viticulture

Marco Lutz [a,*], Daniel Heßdörfer [b], Tobias Ullmann [c], Melanie Brandmeier [a]

[a] *Technical University of Applied Sciences Würzburg-Schweinfurt, Faculty of Plastics Engineering and Surveying, Germany, marco.lutz@thws.de*
[b] *Bavarian State Institute for Viticulture and Horticulture (LWG), Germany*
[c] *University of Würzburg, Department of Remote Sensing, Institute for Geography and Geology, Germany*

* Corresponding author

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Abstract:

The prediction of photosynthetic parameters is crucial for precision viticulture, as it allows for the monitoring of plant physiological status and supports informed management decisions. This research integrates multi-temporal ground-based hyperspectral data and aerial remote sensing to predict key physiological and hydraulic traits, including assimilation rate (A), effective photosystem II quantum yield (ΦPSII), electron transport rate (ETR), and water status parameters such as stem and leaf water potential as well as transpiration and stomatal conductance, in Vitis vinifera within an experimental vineyard in Lower Franconia, Germany (49.92332°N, 9.81944°E). The underlying data framework combines high-resolution diurnal measurements conducted over three separate days in summer 2024 with subsequent comprehensive weekly field campaigns initiated during the 2025 season (starting at pre-veraison, BBCH 71). Ground measurements were captured using a LI-COR LI-6800 gas exchange system and a Spectral Evolution PSR+ hyperspectral spectroradiometer, while scaling to aerial platforms was executed via a 10-band UAV multispectral camera. Both campaigns yielded 180 data points respectively, bringing the total dataset to 360 measurements.

To process these multi-year datasets, multiple machine learning models (Support Vector Regression (SVR), Lasso, ElasticNet, Ridge, Partial Least Squares Regression (PLSR), a simple Artificial Neural Network (ANN), and Random Forest) are optimized and integrated into a stacked ensemble architecture utilizing a Random Forest meta-model. This approach was designed to balance linear interpretability at the base level with non-linear complexity for second-level feature integration. Initial evaluations indicate that the inclusion of first-derivative reflectance (FDR) can significantly enhance prediction performance, particularly for ΦPSII and A, yielding R^2 values up to 0.92 and 0.85, respectively, at 1 nm resolution. While reducing the spectral resolution to coarser scales (5–100 nm) caused an accuracy decline, most parameters, including hydraulic traits and water status appeared to remain robust, and FDR preprocessing could potentially mitigate these performance losses.

While initial diurnal patterns from the 2024 baseline established optimal ground-based monitoring windows, the current focus centers on integrating multi-temporal 2025 weekly datasets to incorporate broader phenological variance. We expect that this broader data integration can transition the existing framework into robust, date- and daytime-independent predictive models, overcoming the temporal constraints of single-day observations. By synthesizing comprehensive ground truths across consecutive growing seasons, this multi-year approach is expected to enable the calibrated transfer of ground-based hyperspectral signatures directly to aerial remote sensing platforms.

The subsequent deployment of the 10-band UAV multispectral camera serves as the critical step for spatial scaling, testing how effectively the established feature pass-through stacked ensembles and first-derivative preprocessing algorithms might transfer from continuous 1 nm ground profiles to discrete, aerially captured bands. Consequently, this study aims to demonstrate a scalable, end-to-end methodology that could bridge the gap between high-resolution proximal sensing and cost-effective, real-time aerial physiological assessments, potentially providing a flexible framework for operational, vineyard-scale precision management under varying environmental conditions.

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