

HYDRA-EO: A Digital Twin component for multi-stressor crop disease detection using earth observation, radiative transfer modeling, and hybrid machine learning

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ABSTRACT :

Agricultural systems are increasingly exposed to interacting biotic and abiotic stressors, making early detection essential to support resilience and sustainable production. The HYDRA-EO project funded by ESA develops a Digital Twin Earth Component that integrates multi-scale Earth Observation (EO), radiative transfer modelling (RTM), and hybrid machine-learning approaches to monitor crop health under real field conditions. The HYDRA-EO framework combines UAV hyperspectral and thermal imagery, airborne campaigns, and multispectral and hyperspectral satellite data (e.g., Sentinel-2, PRISMA, EnMAP, FLEX-like SIF products, CHIME simulator, ECOSTRESS) to retrieve structural and functional plant traits related to stress responses within a physically based RTM approach. A key component of HYDRA-EO is its hybrid machine-learning framework, which uses RTM-based simulations to inform ML models, enabling robust and generalizable prediction of stress indicators across crop types, environmental gradients, and sensor resolutions. This allows the Digital Twin to simulate what-if scenarios, track the progression of diseases and drought stress, and assess the impact of spectral and spatial degradation on trait retrieval. The biotic stress scenarios under contrasting water regimes across European crop systems focus on high-priority pathogens for the EU, including *Flavescence Dorée* in vineyards, Potato Virus Y in potato, and major fungal diseases in pistachio (*Septoria* leaf spot, *Botryosphaeria* canker). All crop scenarios will be assessed using leaf-level physiological measurements and visual inspections to ensure robust validation across crops and environments. HYDRA-EO provides a scalable Digital Twin Component that supports agricultural decision-making and advances Digital Twin Earth through improved EO-based trait modelling and predictive multi-stressor analytics.