[F] PhD Extended Abstract Form

INTEGRATING DRONE-BASED REMOTE SENSING, MACHINE LEARNING AND BAYESIAN MODELING TO ADVANCE PRECISION AGRICULTURE.

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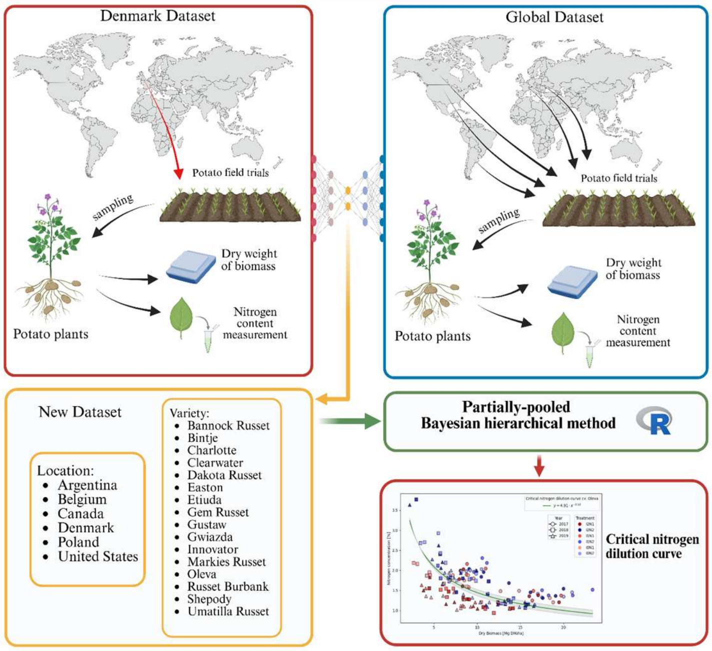
Extended Abstract

This thesis addresses one of the central challenges of contemporary agriculture: how to increase the precision, efficiency and sustainability of crop management under conditions of climatic pressure, input scarcity and strong spatial variability within fields. It investigates the integration of drone-based remote sensing, machine learning and Bayesian modelling as a unified framework for precision agriculture, with applications across horticultural, arable and perennial systems in Europe. The work is structured around a systematic review and a series of applied case studies focused on crop health and stress monitoring, biophysical parameter estimation, yield mapping and the generation of prescription maps. The core premise is that high-resolution UAV data become substantially more valuable when coupled with algorithms capable of modelling nonlinear relationships, preserving spatial structure and explicitly quantifying uncertainty.

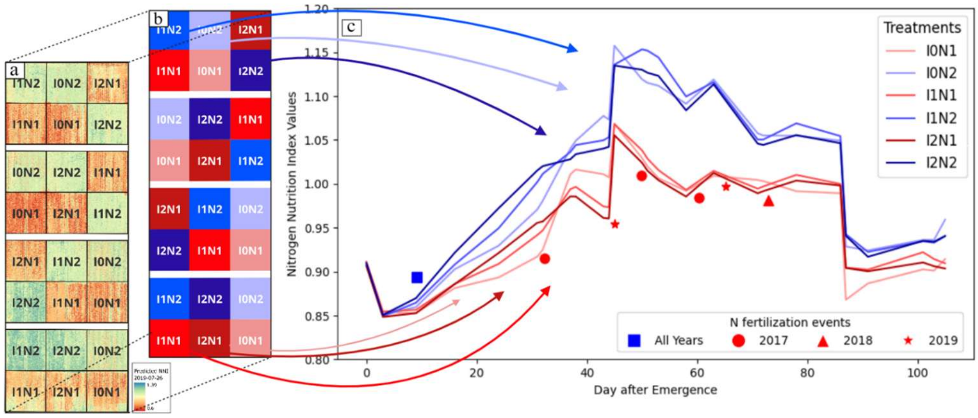
The thesis first establishes its conceptual basis through a PRISMA-based systematic review of UAV applications in vegetable crops. From an initial set of 864 records, 132 studies published between 2018 and 2023 were selected and analysed. The review showed that UAV use in horticulture has expanded rapidly, with crop health and stress monitoring emerging as the most studied application domain, while Solanaceae represented the most investigated crop family. Across the literature, RGB, multispectral, hyperspectral, thermal and LiDAR sensors were used for crop and weed detection, phenotyping, disease scouting, water management, biomass and yield estimation, and aerial spraying.

Overall, the review demonstrated that UAV systems can support earlier diagnosis of crop stress and more targeted interventions, thereby reducing fertiliser, herbicide, pesticide and water use, while also identifying current limitations linked to preprocessing complexity, data fusion, interpretation and operational scalability.

Building on this framework, the thesis develops an original pipeline for precision nitrogen management in potato. A partially pooled hierarchical Bayesian approach was used to estimate the critical nitrogen dilution curve from multi-year experimental data, generating robust ground-truth values of the Nitrogen Nutrition Index even under heterogeneous and partially imbalanced datasets (Fig. 1).



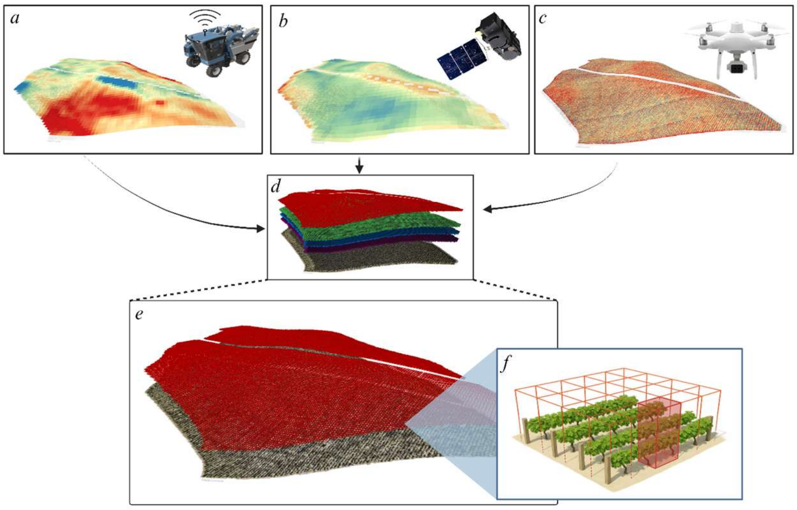
These NNI estimates were then linked to UAV multispectral observations through six machine-learning models. Among them, Gaussian Process Regression performed best, reaching $R^2 = 0.83$ and RMSE = 0.10, and enabling the production of 28 high-resolution NNI maps at 0.04–0.09 m spatial resolution. The resulting maps captured within-season nitrogen dynamics, discriminated among management regimes and revealed strong intra-field variability in nitrogen requirement (Fig.2).



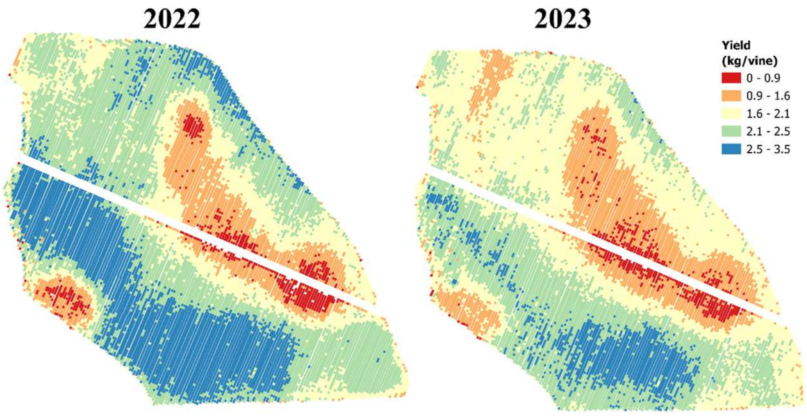
This case study shows that UAV sensing can move beyond descriptive vigour assessment and support actionable, uncertainty-aware nitrogen management with implications for nitrogen use efficiency and the reduction of environmentally harmful losses.

A second major contribution concerns perennial crops, especially vineyards and olive groves, where the thesis combines physiological, structural and spatial analyses to improve crop monitoring. In vineyards, multispectral and thermal imagery captured stable patterns of canopy vigour and temperature, hyperspectral reflectance enhanced the discrimination of grapevine varieties, and UAV-LiDAR robustly reconstructed canopy architecture, with point-density metrics strongly associated with canopy and leaf area. In parallel, pruning weight showed significant relationships with multispectral indices, especially before ripening, and could be mapped effectively through regression and ordinary kriging. In olive groves, UAV multispectral surveys detected vigour responses linked to pruning and supported tree-level analysis of canopy condition, indicating that drone-based sensing can support not only diagnosis but also more automated and spatially differentiated management in perennial systems.

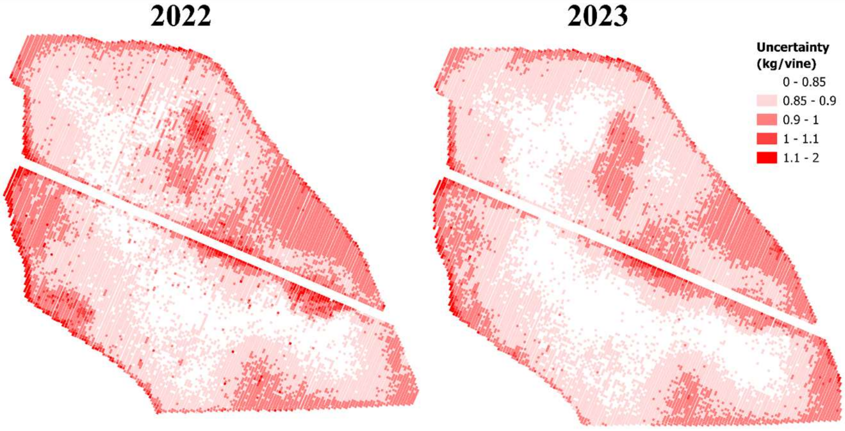
The most advanced predictive application presented in the thesis is Bayesian vineyard yield mapping. A hierarchical partially pooled Bayesian model implemented in brms integrated UAV-derived NDVI, Sentinel-2 NDVI and grape-harvester telemetry to generate high-resolution yield maps with explicit prediction uncertainty (Fig.3).



The best model achieved R^2 = 0.83 and RMSE = 0.26 kg vine^{-1} on training data, and R^2 = 0.78 in independent validation. It also detected an approximately 15% yield decline in 2023 associated with drought and heat stress, while preserving stable spatial patterns related to pedological variability (Fig. 4).



Uncertainty was not spatially uniform, but increased near field boundaries and in areas where predictors diverged, making the model useful not only for prediction but also for guiding targeted field inspections and more transparent agronomic decision-making (Fig.5).



The thesis also makes an important methodological contribution by showing that the quality of ground-truth sampling design substantially affects UAV-based modelling performance. In vertically shoot-positioned vineyards, reference data based on contiguous one-metre canopy segments outperformed conventional vine-based sampling across linear models, machine-learning algorithms and Bayesian inference. The linear-segment approach achieved markedly better accuracy, with R^2 values around 0.78–0.84 and RMSE close to 0.26 kg m^{-1}, while also reducing posterior uncertainty. This result is particularly relevant because it demonstrates that reliable remote-sensing prediction depends not only on sensor resolution or algorithm selection, but also on the geometric coherence between the sampling unit and the canopy footprint observed by the UAV. The thesis therefore contributes both new predictive frameworks and improved experimental protocols for scalable field applications.

Finally, the research translates sensing outputs into direct management tools. In potatoes, NNI and nitrogen requirement estimates were converted into high-resolution prescription maps for variable-rate fertilisation. In olive orchards, UAV multispectral imagery supported GIS-based fertilisation strategies that reduced nitrogen use by 24% and 33% compared with standard uniform fertilisation. Across the thesis, therefore, drone-derived products are treated not merely as diagnostic layers but as decision layers that can directly inform fertilisation, pruning, irrigation and harvest management. Overall, this work demonstrates that the integration of UAV sensing, machine learning and Bayesian modelling provides a robust and scalable foundation for precision agriculture, capable of producing spatially explicit, uncertainty-aware and operationally relevant outputs. Future progress will depend on the standardisation and automation of preprocessing, broader multi-site validation across crops and environments, stronger multi-sensor fusion, and the development of user-friendly tools that embed model recommendations and uncertainties into real farm workflows. Under these conditions, the framework proposed in this thesis offers a realistic pathway from research to field-ready decision support, helping align agronomic performance with environmental sustainability.

Final remarks concerning benchmarks and strength points of the the Pellizzi Prize 2026

This thesis matches the benchmarks of the Pellizzi Prize by addressing agricultural machinery and mechanization innovation through an integrated framework combining UAV-based sensing, machine learning and Bayesian modelling. Its main strength lies in the originality of transforming high-resolution remote-sensing data into operational decision tools, including yield maps, nitrogen status maps and variable-rate prescription maps. The work has clear transfer potential, because the proposed methods support practical management of fertilisation, irrigation, pruning and harvest. The expected benefits for agriculture and farmers are concrete: lower input use, reduced losses, improved timing of interventions, stronger spatial targeting, and transparent uncertainty-aware decisions that enhance both profitability and environmental sustainability.

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