



AI Fruit Cracking Risk Prediction Models: A Multi-Country UAV Framework for Predicting Yield and Fruit Loss

Fruit cracking causes major economic losses in high-value crops, yet it remains difficult to predict because it results from complex interactions among weather, irrigation, and plant physiology. Within the CrackSense project, we developed a harmonized multi-country framework that combines UAV remote sensing, field physiological measurements, and weather data to estimate plant water status (PWS), predict yield and fruit cracking, and support orchard management across Israel, France, Greece, and Germany. The core innovation is the integration of tree-level indicators, stem water potential, trunk growth, stomatal conductance, and canopy structure, with multispectral, thermal, and LiDAR sensing, providing an operational pathway from monitoring to actionable cracking-risk management.

Introduction

Fruit cracking causes substantial economic losses in high-value perennial crops because damage often appears late, varies strongly within orchards, and results from complex interactions among heat, irrigation, crop load, and tree physiology. These processes are further intensified by climate variability, underscoring the need for timely, spatially explicit monitoring tools. CrackSense addressed this challenge by moving beyond single indicators and developing a common analytical framework that links plant water status (PWS) to cracking outcomes across crops, environments, and management systems. The project combined standardized methodologies with site-specific implementation across four countries: Israel (citrus, pomegranate, table grapes); France (citrus, sweet cherry); Greece (pomegranate, table grapes); and Germany (sweet cherry). Across all sites, monthly or stage-based UAV campaigns were synchronized with key phenological phases, while field physiological measurements, weather observations, and management records were collected in parallel. Country contributions included:

1. Israel - Citrus, pomegranate, and table grapes; the most complete end-to-end demonstrations, including Random Forest modelling, deep learning of tracking by detection, and orchard management zoning.
2. France - Citrus and sweet cherry; integration of remote sensing, weather-driven feature engineering, and structured validation workflows.
3. Greece - Pomegranate and table grapes; Random Forest modelling under Mediterranean orchard conditions.

This multi-country design transformed individual case studies into a transferable methodology for predicting cracking risk and supporting precision orchard management across diverse agro-climatic conditions.



Methodology

The CrackSense methodology was built as a five-stage workflow that links field observations, environmental data, UAV sensing, and artificial intelligence to predict PWS, yield, and fruit cracking risk (Fig. 1). First, reference trees were monitored using direct physiological measurements, including stem water potential from pressure chambers, stomatal conductance from a porometer, trunk growth and maximum daily shrinkage from dendrometers, and plant area index derived from field measurements and LiDAR. Second, these observations were complemented by weather, soil, and irrigation data, including air temperature, relative humidity, rainfall, vapor pressure deficit, growing degree days, soil water content, and irrigation records. Together, these variables provided the environmental and management context needed to interpret stress dynamics and treatment effects throughout the season.

Third, UAV campaigns were conducted using multispectral, thermal, and LiDAR sensors to capture canopy condition and spatial variability within orchards. Multispectral imagery was calibrated to surface reflectance using empirical line calibration, and vegetation indices such as NDVI, GNDVI, NDRE, EVI, and SAVI were extracted. Thermal imagery was converted to canopy temperature and normalized into the Crop Water Stress Index (CWSI), enabling comparisons across dates and atmospheric conditions. LiDAR point clouds were processed through ground classification, height normalization, canopy height modeling, and individual-tree segmentation to derive crown area, canopy height, and structural proxies such as plant area index and leaf area density. Finally, all field, UAV, meteorological, and management variables were aggregated at the tree level and used for predictive modelling. Random Forest was the primary machine-learning method because it handled nonlinear relationships, mixed data types, and correlated predictors effectively under limited sample sizes, while XGBoost, ANN, and SVR were also evaluated. Feature selection and interpretation were supported by Boruta, variance inflation factor filtering, variable importance analysis, and, in some workflows, SHAP analysis. The resulting PWS predictions were then linked to final yield and cracking outcomes, enabling identification of critical stress windows and spatially explicit risk zones for targeted orchard management.

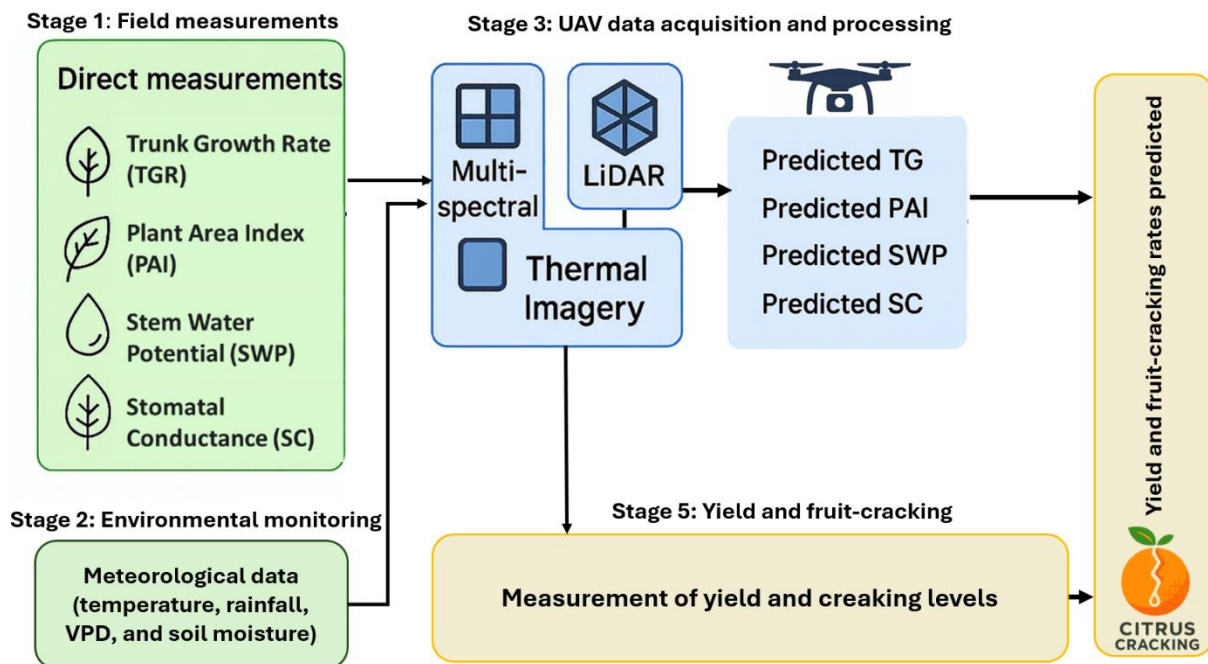


Figure 1. Project-wide sensing and modelling workflow used across CrackSense sites.

In this report, we present representative tree-level modeling results for citrus and pomegranate in Israel, highlighting frameworks developed for yield prediction and fruit cracking assessment.

Linking Plant Water Status Dynamics to Yield and Fruit Cracking in Citrus Orchards Using UAV Multi-Sensor Data and Machine Learning

Accurate prediction of fruit cracking and yield is essential to improve profitability and water management in citrus orchards amid increasing climate variability. We developed a tree-scale framework integrating UAV multispectral, thermal, and LiDAR data with field physiological measurements to estimate plant water status (PWS), yield, and fruit cracking in a commercial 'Ori' mandarin orchard under contrasting irrigation regimes over two growing seasons. Reference trees were monitored for stem water potential (SWP), stomatal conductance (SC), trunk growth (TG), and plant area index (PAI), while UAV campaigns captured canopy reflectance, canopy temperature, Crop Water Stress Index (CWSI), and structural traits. Random Forest models outperformed XGBoost, ANN, and SVR for predicting PWS indicators, achieving validation R^2 values of 0.83 for TG, 0.85 for SWP, and 0.85 for SC. These predicted physiological indicators were then used to estimate final yield and cracking incidence. Yield models achieved strong performance ($R^2 = 0.913$), while cracking models were similarly robust ($R^2 = 0.851$). Mid-season SC, SWP, and TG were the dominant predictors of yield, whereas July-September SWP was the strongest predictor of fruit cracking. Higher irrigation increased yield but also elevated cracking risk, highlighting the trade-off between productivity and fruit quality. Seasonal clustering of PWS trajectories further identified orchard management zones with distinct stress responses. The results demonstrate that integrating UAV sensing with physiology-based machine learning provides an operational pathway for precision irrigation and cracking-risk management in citrus orchards.

Predicting Pomegranate Yield and Fruit Cracking from Plant Water Status Using UAV Remote Sensing and Machine Learning

Fruit cracking is a major constraint in pomegranate production, yet its relationship with plant water status and canopy structure remains poorly quantified at the orchard scale. This study developed a multi-sensor UAV framework to predict yield and cracking in commercial pomegranate orchards by linking remote sensing indicators with physiological stress responses. Repeated UAV campaigns acquired multispectral, thermal, and LiDAR data across key phenological stages, while irrigation treatments created contrasting water-stress conditions. Tree-level structural, spectral, and thermal metrics were integrated with field measurements of plant water status and final harvest observations. Random Forest models were used to estimate yield and cracking responses under variable environmental and irrigation conditions. Results showed that canopy structural traits, particularly plant area (PA), were the most informative predictors of cracking rate, indicating that tree architecture strongly influences fruit susceptibility. Thermal and multispectral indicators further improved model robustness by capturing canopy stress and yield. The combined framework successfully identified trees and zones with elevated cracking risk while simultaneously predicting spatial yield variability. These findings demonstrate that pomegranate cracking can be predicted as a measurable physiological and structural process rather than only observed at harvest. The proposed methodology offers a practical tool for targeted irrigation, canopy management, and yield protection in high-value orchards under warming climates.

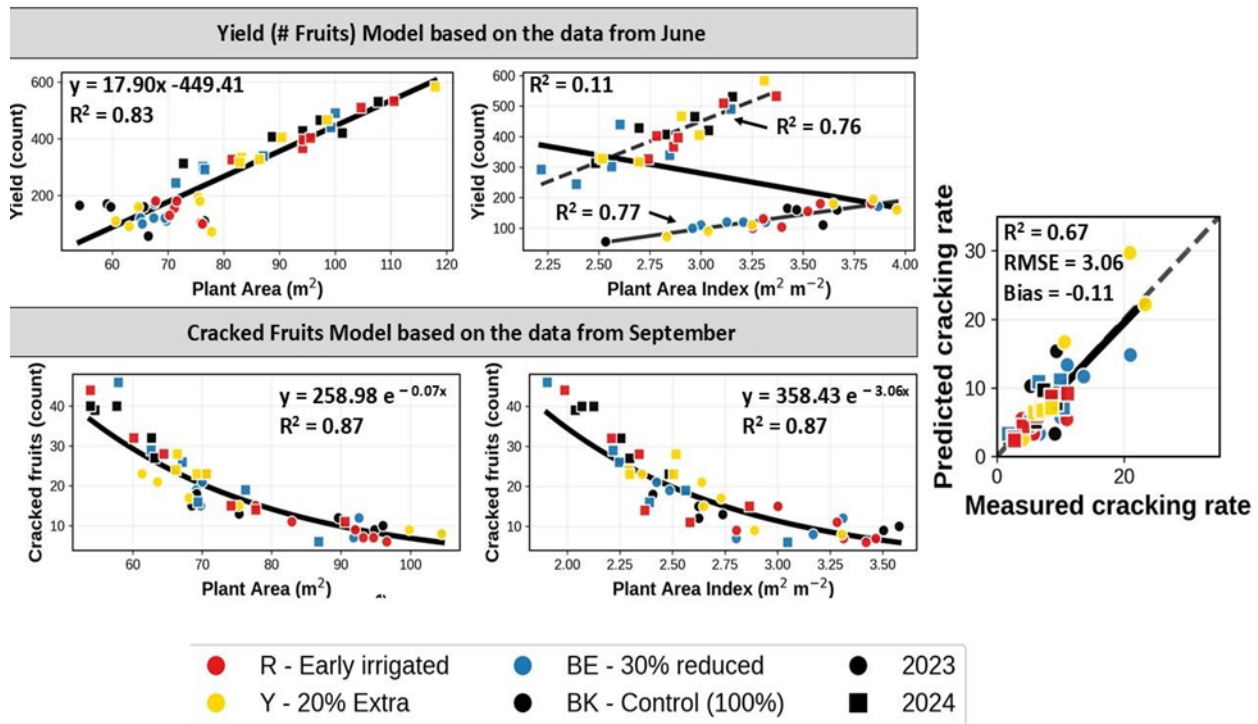


Figure 2. The correlation between Plant Area (PA) and Plant Area Index (PAI), yield, and cracking rate in Tso'ra, Israel.

A Tracking-by-Detection Framework for Tree-Scale Estimation of Pomegranate Fruit Load and Loss from UAV Imagery

Fruit cracking causes significant production losses in pomegranate (*Punica granatum* L.) orchards, yet most vision-based yield estimation systems focus only on healthy fruit counts and overlook defective or dropped fruits, limiting their usefulness for orchard management and marketable-yield forecasting. We present a tracking-by-detection framework that jointly estimates fruit load and fruit loss at the individual-tree level using UAV RGB video. The approach integrates deep-learning object detection with multi-object tracking to quantify healthy fruits (fruit load) and defective or dropped fruits (fruit loss), enabling simultaneous estimation of potential production and realized losses. To address the strong class imbalance between abundant healthy fruits and relatively rare, damaged fruits, two independent single-class YOLO detectors were trained separately and embedded within a unified tracking workflow. UAV videos were collected using a forward-facing inter-row flight configuration designed to reduce interference from adjacent rows through acquisition geometry rather than post-processing filters. Each tree was recorded from both sides of the canopy. Fruit-load estimates were derived from the maximum count across the two views to minimize double-counting, whereas fruit-loss estimates were obtained by summing detections from both views because ground-level losses were only partially visible from a single side.

Multi-object tracking further stabilized counts across frames and reduced duplicate detections caused by fruit persistence in consecutive images. The framework was evaluated across three commercial plots in two orchards under contrasting canopy structures and fruit-loss levels. Mean absolute errors of 20.5 fruits tree⁻¹ for fruit load and 4.33 fruits tree⁻¹ for fruit loss were achieved, with strong predictive performance for fruit-loss estimation ($R^2 = 0.913$) and moderate performance for fruit-load estimation ($R^2 = 0.595$).

Results indicate that losses associated with cracked and dropped fruits can be quantified more accurately than total fruit load, likely because damaged fruits are fewer, more visually distinct, and less affected by canopy occlusion. By explicitly estimating fruit loss alongside fruit counting, the proposed framework moves beyond conventional yield estimation toward a realistic assessment of marketable productivity. The method provides a scalable, non-destructive solution for rapid orchard phenotyping, harvest planning, and spatial identification of cracking hotspots, supporting data-driven management decisions in high-value perennial crops.

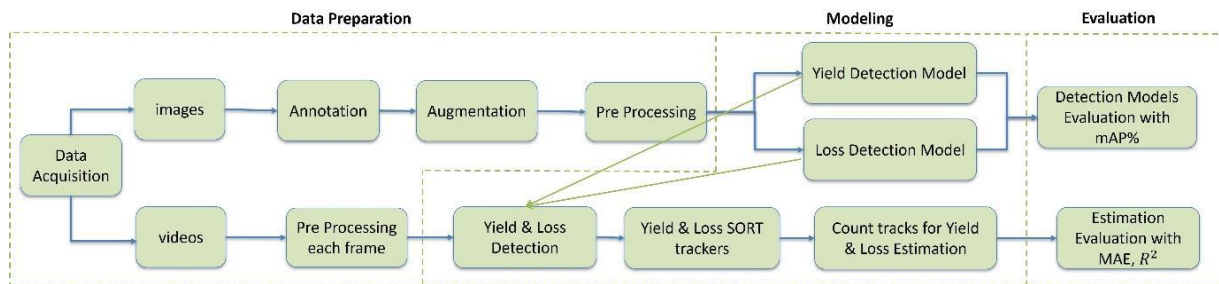


Figure 3. Deep-learning workflow developed for UAV-based pomegranate yield and fruit-loss estimation in Tso'ra, Israel.

A major strength of the project is that these examples were not isolated case studies. The same harmonized framework was implemented across France, Greece, and Germany, with adaptations to crop type, sensor availability, and experimental design. France extended the approach to citrus and sweet cherry using multispectral, thermal, and LiDAR data combined with weather-based feature engineering and structured cross-validation. Greece applied Random Forest modelling to pomegranate and table grapes under Mediterranean orchard conditions. This multi-country implementation is important because it transforms a site-specific workflow into a transferable methodology that can be adapted across crops, climates, and management systems rather than remaining a single-orchard solution. Methodologically, the project demonstrates that fruit cracking can be modelled as a physiologically grounded and spatially explicit process. Rather than treating cracking only as a final symptom observed at harvest, the framework reconstructs the causal pathway from environmental and management drivers, through canopy response and plant water stress, to yield and cracking outcomes. This is what makes the models valuable for decision support: they can identify when stress develops, where it accumulates within the orchard, and which variables contribute most strongly to cracking risk and productivity loss.

Conclusion

The main takeaway is that CrackSense has delivered a general and scalable methodology for sensing-based prediction of fruit cracking across multiple countries, crops, and production systems. Strong and consistent results were obtained across all participating countries, demonstrating the robustness of the framework under diverse agro-climatic conditions, crop types, and management systems. Israel provided the most complete end-to-end demonstrations in citrus, pomegranate, and grapes, while France, Greece, and Germany confirmed that the same harmonized methodology can be successfully transferred and adapted to additional crops and environments. This confirms that the approach is broadly applicable rather than limited to a single site or crop.

A second key insight is that fruit cracking can be predicted as a measurable physiological process. By linking environmental drivers, irrigation management, canopy condition, and plant water status to final yield and cracking outcomes, the framework moves from reactive damage assessment toward proactive orchard management. This enables earlier intervention, improved irrigation scheduling, targeted canopy management, and spatial prioritization of high-risk zones across orchards.

For future deployment, the most important recommendation is to retain the multi-sensor, tree-level, physiology-linked design, as it provides the best balance between biological interpretability, predictive performance, and operational relevance for growers and advisors. Future developments should focus on simplifying data pipelines, integrating outputs into user-friendly dashboards, and expanding toward real-time alerts and seasonal forecasting tools for climate-resilient orchard management.

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