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Executive Summary

This document comprises a detailed report on the final demonstration of the integrated SCADA system capabilities within a real-world (1:1 scale) hazelnut orchard. Notably, this report is supported by two videos which summarize in a footage the experimental validation of the proposed SCADA architecture. In particular, the first video provides an overall description of the main aspects of the SCADA architecture along with the experimental validation of the project objectives, while the second video provides a longer and more detailed description of all the main technical aspects concerning the design, implementation, and experimental validation of the SCADA architecture.

These two videos can be found at the following links:

1. SCADA System Functionalities Description
   https://bartolo.dia.uniroma3.it/assets/final_demo/pantheon_scada_architecture.mp4

2. SCADA System Functionalities Detailed Technical Description
   https://bartolo.dia.uniroma3.it/assets/final_demo/pantheon_scada_architecture_full.mp4

Table of Content

Abbreviations and Acronyms

WP	Work Package
SLAM	Simultaneous Localization And Mapping
EKF	Extended Kalman Filter
KF	Kalman Filter
UI	User Interface
UGV	Unmanned Ground Vehicle
UAV	Unmanned Aerial Vehicle
OP	Orienteering Problem
RTK	Real-time kinematic
IoT	Internet of Things
DCP	Data Collection and Pre-processing
DT	Data Transfer
DSP	Data Storage and Processing
ICP	Iterative Closest Point
API	Application Programming Interface
YOLO	You Only Look Once
NDVI	Normalized Difference Vegetation Index
CWSI	Crop Water Stress Index
SR	Simple Ratio Index
IPM	Integrated Pest Management
qPCR	Quantitative Polymerase Chain Reaction
DoA	Description of Action
YE	Yield Efficiency
TCSA	Trunk-Cross Sectional Area

1 SCADA Sub-Systems

In this section the main results of WP3 “SCADA Sub-Systems Design and Realization” are reported. Specifically, the architectures developed for the ground and aerial robots and the integration of the overall SCADA system are discussed.

1.1 Ground Robot Functionalities

One of the objectives of the project PANTHEON is to develop an Unmanned Ground Vehicle (UGV) capable of moving within an orchard to collect data and perform typical farming operations such as suckers’ management in a fully autonomous manner. Several modules were required to achieve this objective, ranging from the design and implementation of control, navigation, and planning algorithms up to a simultaneous localization and mapping (SLAM) framework.

The two SHERPA HL robotic platforms used within the project PANTHEON were mechanically designed and customized to accommodate different kinematic models to facilitate the specific precision farming activities they are dedicated to. While the SHERPA HL robotic platform R-B has been mechanically designed to operate according to the Ackermann Steering kinematics, the SHERPA HL robotic platform R-A can operate according to both the Omnidirectional kinematics and the Ackermann Steering kinematics. However, experimental validation conducted on the field of Caprarola, highlighted how the Ackermann Steering kinematics model is more suited than the Omnidirectional kinematics model for the navigation of ground robots in a hazelnut orchard.

Figure 1 shows the equipment installed on the SHERPA HL robotic platform R-A whereas Figure 2 shows the equipment installed on the SHERPA HL robotic platform R-B.

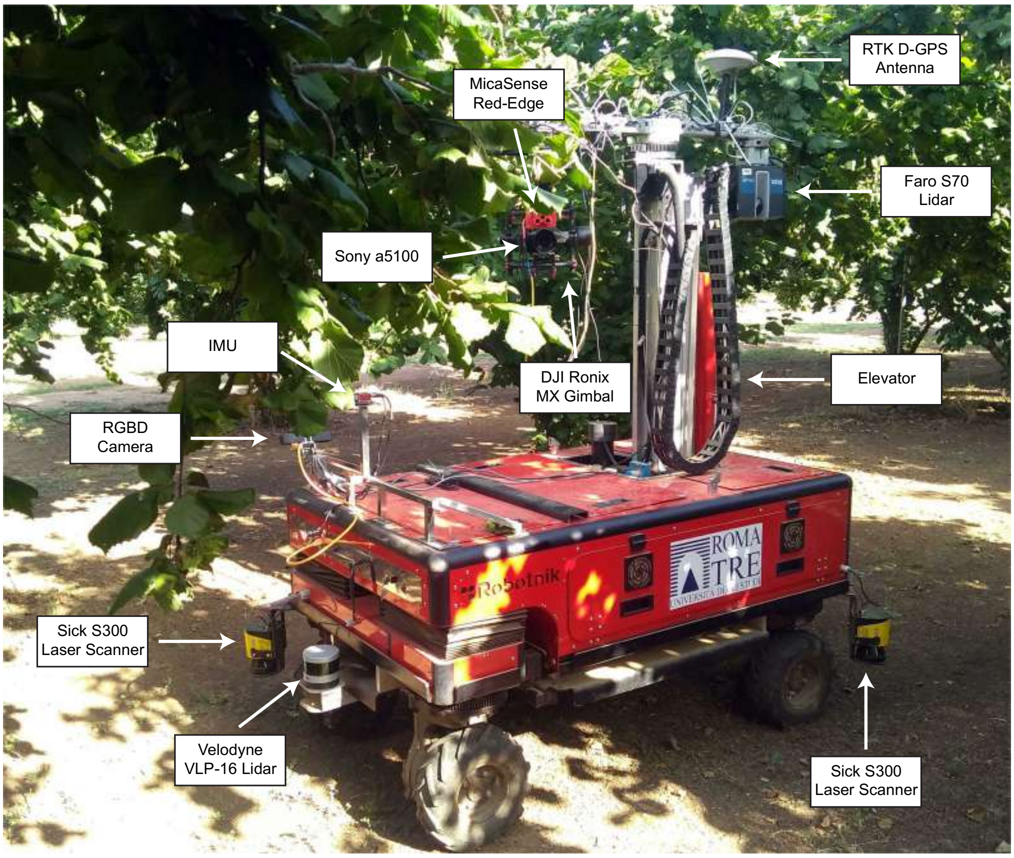

Figure 1. SHERPA HL robotic platform R-A

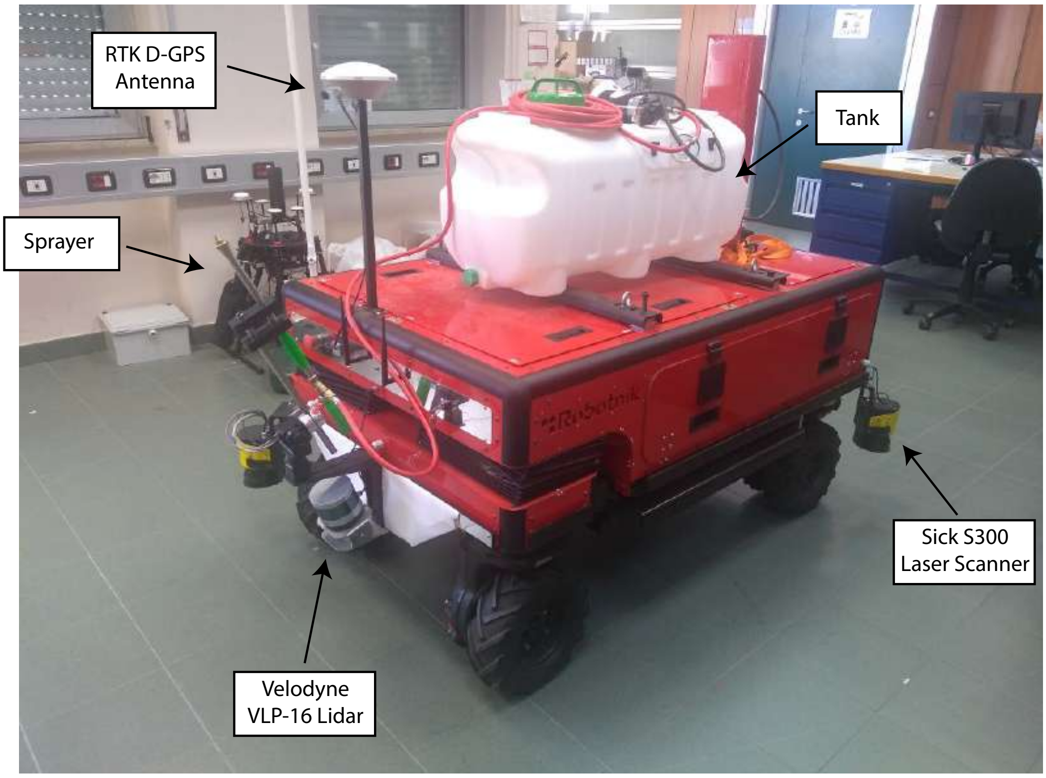

Figure 2. SHERPA HL robotic platform R-B

In the following, we briefly detail the three major modules we developed for the autonomous navigation of the ground robots. The reader is referred to Deliverable D6.1 "Robotic Vehicles Field Validation" [1] for a comprehensive overview of the argument.

The first module required for the autonomous navigation of Ackermann steering vehicles in precision farming settings is the Simultaneous Localization And Mapping (SLAM) architecture. This module relies on two layers: an Extended Kalman Filter (EKF-SLAM) system and a Kalman Filter (KF) which estimates the planting pattern of the target field. The former formulates the problem as a landmark-based map estimation, where each landmark represents an individual tree of the field. At the same time, the KF estimates the planting pattern of the considered field. This problem is formulated by encoding the planting pattern as a chessboard with a rectangular chess fitting process, where the KF aims at estimating the length of the main chess directions and the angle which aligns the chessboard with the geo-referenced map. This estimated pattern is successively exploited during the landmark data association process to distinguish among landmarks and outliers. The latter are modelled as potential obstacles to be avoided and this information is passed to the second module of this architecture.

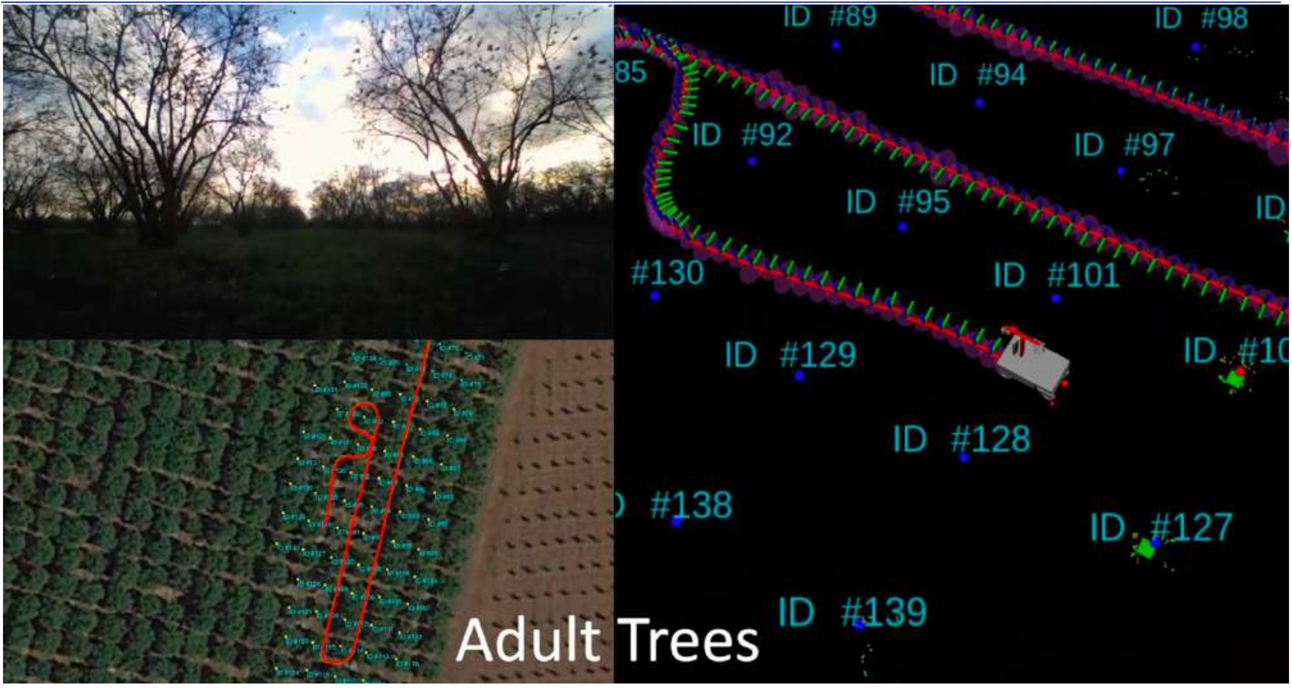

Figure 3. Experimental validation of the SLAM architecture conducted in winter 2021

A local planner is the second module that composes our autonomous navigation architecture. The local planner is in charge of generating in real-time optimal trajectories over a time horizon from any given initial pose and velocity that fulfill the following requirements:

- the trajectory steers the robot to a given target pose;
- the trajectory satisfies the Ackermann kinematics constraints and is collision-free;
- the trajectory is generated in a receding horizon fashion and in real-time.

Optimal trajectories that fulfill the above requirements are formulated solving iterative minimization problems over a finite time horizon. Notably, the local planner is also able to account for dynamics obstacles that may appear in the path of the robot thanks to an obstacle detection algorithm purposely designed for the precision farming setting considered within the project PANTHEON.

The third module of the autonomous navigation architecture is a non-smooth control law that is able to steer the robot from any initial configuration to any desired pose, making it capable of tracking closely the planned optimal trajectory. Since experimental validations have demonstrated that the Ackermann Steering Kinematics model is the more effective for autonomous navigation in our precision farming setting, the proposed control law is based on this model. The reader is referred to Deliverable D3.1 “3D Tree Models” [2] for further details.

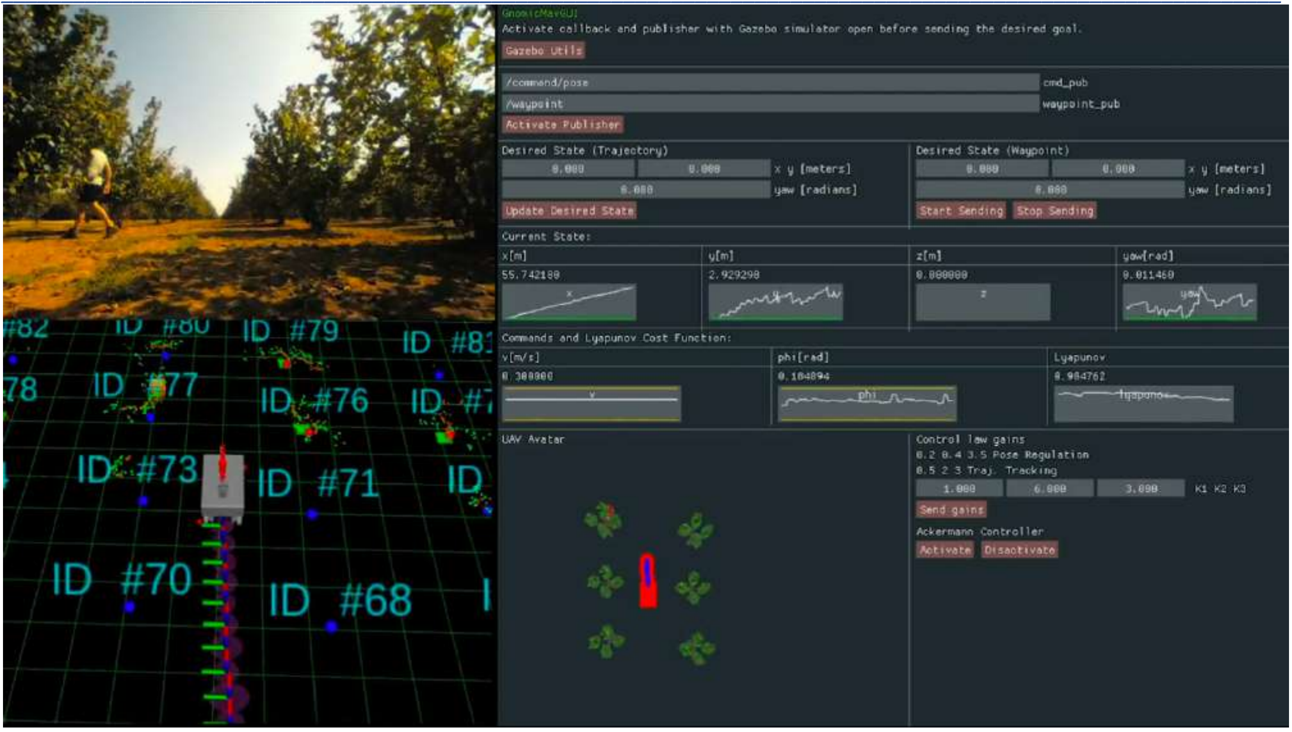

Figure 4. Local planner and controller validation conducted in summer 2021

The autonomous navigation architecture has been fully validated in many numerical simulations and many experimental campaigns conducted in the real-world hazelnut orchard of the project PANTHEON (Figure 3 and Figure 4).

Contribution to the State of the Art

The functionalities developed for the ground robots have extended the state of the art in several research topics, as described in the following.

The proposed SLAM architecture addresses the localization and mapping problem in large-scale orchards. This module of the proposed autonomous navigation architecture is a compact and hierarchical Simultaneous Localization And Mapping system purposely designed for this specific setting. Since the standard SLAM approaches may not properly scale with the field extent from both a memory footprint and computational complexity perspectives or environmental conditions may drastically change across the seasons, it was necessary to design a tailored SLAM architecture to address these problems. We address the memory footprint problem by formulating the map as a set of landmarks, where each landmark represents an individual tree in the considered orchard. To keep a constant computational complexity, we employ a dynamic partitioning strategy which, for each update step, makes use of just a partition of the map. Moreover, we also estimate the planting pattern of the considered field and exploit this information as a cue in the outlier detection process, also rendering the proposed approach capable to detect dynamic obstacles to avoid during the navigation within the field. Experiments show how the proposed SLAM architecture is robust to the different seasonal conditions of the considered environment and, moreover, offers good localization and mapping capabilities even in the absence of the RTK-GPS signal. The SLAM architecture is the subject of a manuscript that is now in preparation for publication [3].

The local planner addresses the trajectory planning problem. This planner generates in real-time a sequence of successive poses that steers the robot towards its desired location while avoiding all the surrounding obstacles, satisfying the trajectory required by the controller. The planning problem is formulated as a real-time cost-function minimization problem over a finite time horizon where the Ackermann kinematics and the presence of obstacles are encoded as constraints. In addition, the proposed planner is reliable even in the case of dynamic obstacles suddenly appearing along the planned route. The proposed controller addresses the problem of the pose regulation. This module ensures the convergence toward each of desired poses with a high level of accuracy. This result can be reached with a novel non-smooth control law designed to ensure the solvability of the pose regulation problem for the Ackermann Steering vehicle. In particular this controller is capable to perform complex maneuvers even in the absence of a trajectory planner. The planner and controller results have been published in [4].

1.2 Aerial Robot Functionalities

The objective of the developed aerial robot unit is to be able to obtain remote sensing measurements of the phytosanitary status of the orchard from different kind of sensors, used simultaneously or separately, while ensuring a high accuracy and quality of the obtained data.

The UAV subsystem has been developed to be able to integrate three different kinds of sensors in a single flying platform: an RGB camera, a multispectral camera, and a thermal camera. These three sensors are controlled by an onboard computer which is also in constant communication with the flight controller of the UAV.

Figure 5 shows the equipment installed in the DJI M600 drone.

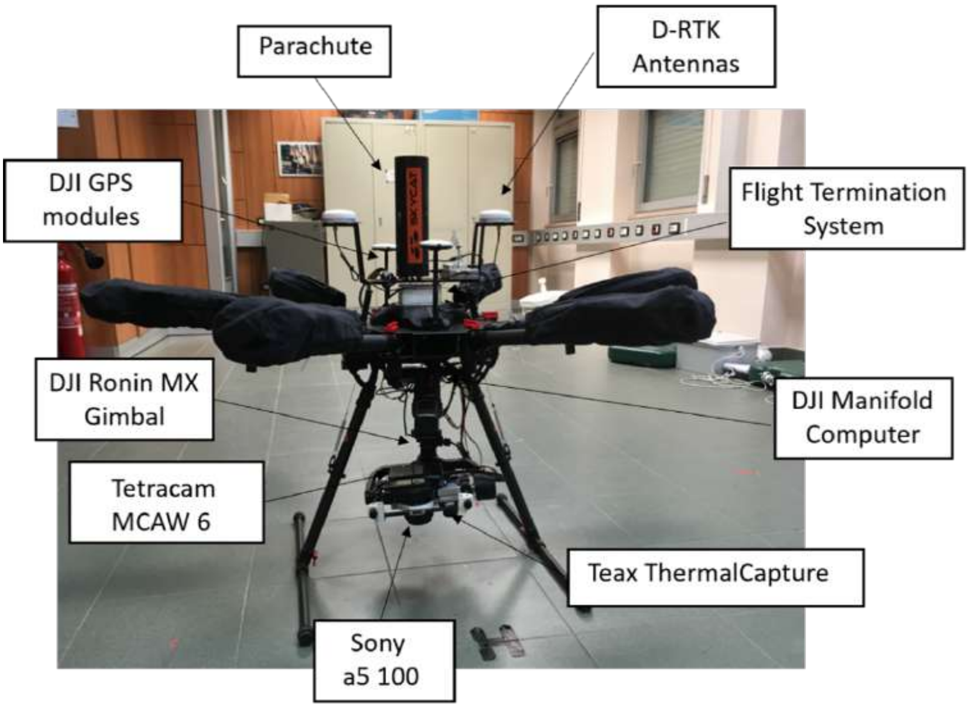

Figure 5. DJI M600 drone

During the flight mission, the UAV subsystem is connected via two wireless communication channels with the Radio controller and a system terminator, respectively. Additional connections with a workstation have been avoided due to security reasons and interferences created by the system.

The system implemented computes an optimal mission based on the cameras used, relying on their field of view and the desired overlap, and triggers the selected cameras and the appropriate instants. The mission is computed offline and transferred to the UAV before the flight. This procedure has shown to be the best in terms of reliability and security during the sensing missions.

The UAV uses an RTK base station to correct the local position of the UAV during the flight and to provide an accurate path. To ensure the quality of the obtained data, the onboard computer also records the UAV data associated to each measurement providing a log file that can be used in the post processing of the data to obtain orthomosaics of high quality.

It must be noted that the implemented UAV subsystem is not directly connected to the rest of the SCADA system during the flight operation, and that the data is later transferred to the server. This decision responds to the current UAV regulations that are very strict regarding the human control of the UAV during every mission, and which make the use of completely autonomous missions not possible at the moment. Based on that, in the developed system, the central unit informs of a remote sensing mission on the area and then receives the data to be analyzed. We believe that this procedure is more suitable for a near-future implementation of the system.

The data acquisition campaigns for UAVs have been planned through the user application, as well as the rest of the agronomic activities and the UGV acquisition missions. The mission definition allows to specify details such as the platform to be used, which sensors to use, the data collection targets and the day of execution of the activity.

At runtime, the navigation system allows the autonomous movement of the drone with operator supervision. The scanning system carries out data collection by flying over the target mission area. The scanning and detection processes save the collected data on local memory which are then transferred to the server.

The reader is referred to Deliverable D6.1 “Robotic Vehicles Field Validation” [1] for further details.

Theoretical achievements

The theoretical research carried out on the UAV platform has been focused on the development of more efficient path planning strategies. This line of research aims at reducing the flying time required to cover a given extension of field and therefore to increase the size of the area covered by flight.

This algorithm has been developed after observing that the main limiting factor for an appropriate monitoring of the orchard was related to the autonomy of the UAV. The main problem is that current path planning strategies consider an exhaustive and complete coverage, which results in time consuming missions for relatively small portions of field.

After exploring different alternatives and evaluating the available literature, we developed an algorithm that optimizes the path according to the information available, based on the previous measurements and the knowledge of the dynamics of the system monitored. We assume that the monitoring area has certain dynamics and statistical properties that are known. In this regard, the planning strategy only covers a portion of the area of interest, and the remaining elements are estimated based on the dynamics of the system and the spatial correlation between measurements.

The path planning policy is obtained as part of the estimation process of the monitored phenomena. This is achieved by structuring it as an Orienteering Problem (OP). The Orienteering Problem is a combinatorial problem which consists of a node selection where the shortest path in between the selected nodes is determined. Given a time or length constraint, the objective is to maximize the score given by the visited points. UAV remote sensing activities, due to the flight time restriction and the discrete nature of the measurements, are likely to be adapted as an OP. In this context, the set of points represents the possible measurement coordinates, the time interval is adapted to the vehicle autonomy, and the cost function is some measure related to the measurement point.

The main contribution of this work is the inclusion of the update step of the Kalman filter estimation as part of the Orienteering Problem. This is done by resorting to a formulation based on the Fisher information matrix. The main advantage of this approach is that the path of the mobile sensor is computed taking into account the process dynamics, the estimation uncertainty and the existing fixed sensing structure. By doing so, it allows to define the optimal combination of the UAV remote sensing with additional sensing devices by resorting to an observer-based architecture.

The developed strategy provides an offline computation of the optimal sensing points over one step ahead horizon of the estimation process. This approach allows to obtain the optimal path in cases where the coverage is done with unknown periodicity or when the time gap between flights is too large.

1.3 Software Architecture

In the following the software architecture at the base of the proposed SCADA system for precision farming is described. Further details can be found in the Deliverable D6.2 “SCADA System Integration and Field Validation” [5].

Defined Architecture

The developed architecture of the data collection and processing system is shown in schematic form in Figure 6 and is composed of three main components, which implement three operational levels:

- The “Data Collection and Pre-processing” layer (DCP layer): this component should be replicated for each hazelnut field and is dedicated to the collection of data from the various sources located in the field: sensors, weather stations, ground robots (UGV) and drones (UAV).
- The “Data Transfer” layer (DT layer): this is a middleware that deals with the transfer of data between the other two levels, in both directions, and between the overall system and the final users of the software;
- The “Data Storage and Processing” layer (DSP layer or center in the following): it consists of a centralized unit in which all the data coming from the various DCP components are stored and on which massive analyses are carried out, mainly for knowledge extraction and decision support.

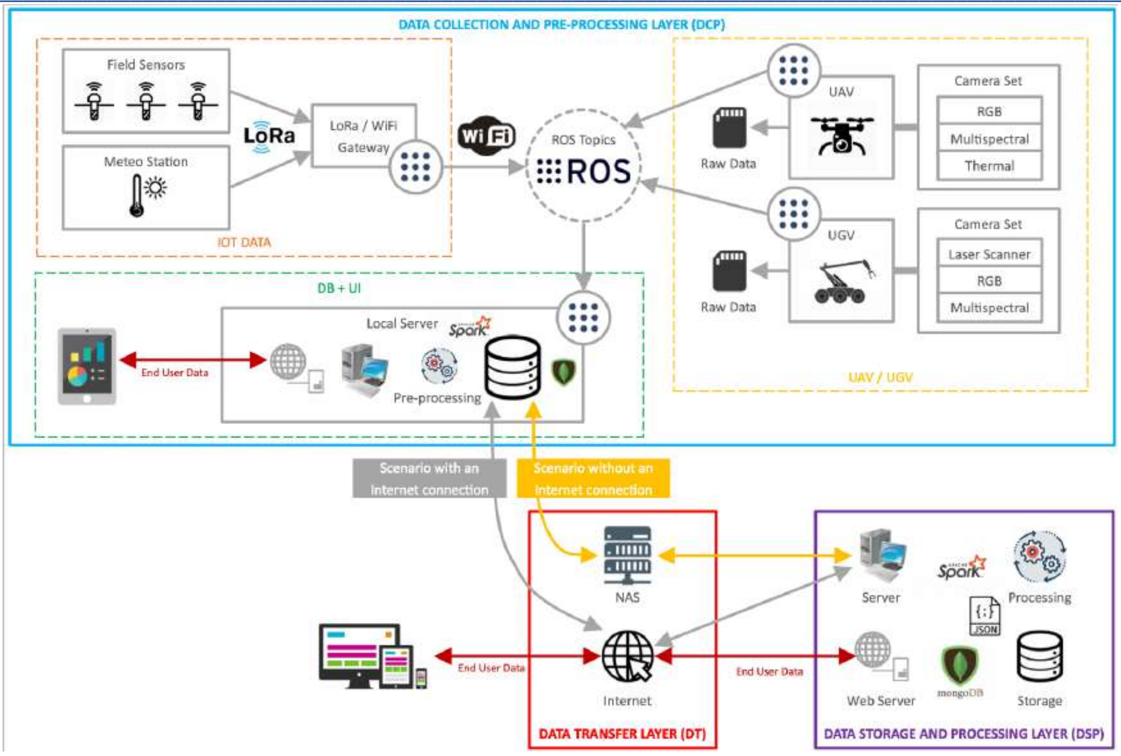

Figure 6. The global architecture of the software system

The defined architecture allowed to drive the development of the various components in order to implement the necessary data flow.

In the diagram in Figure 7, the data flow through the various levels: Data source, Local server, Analysis Server and Analysis (Processing).

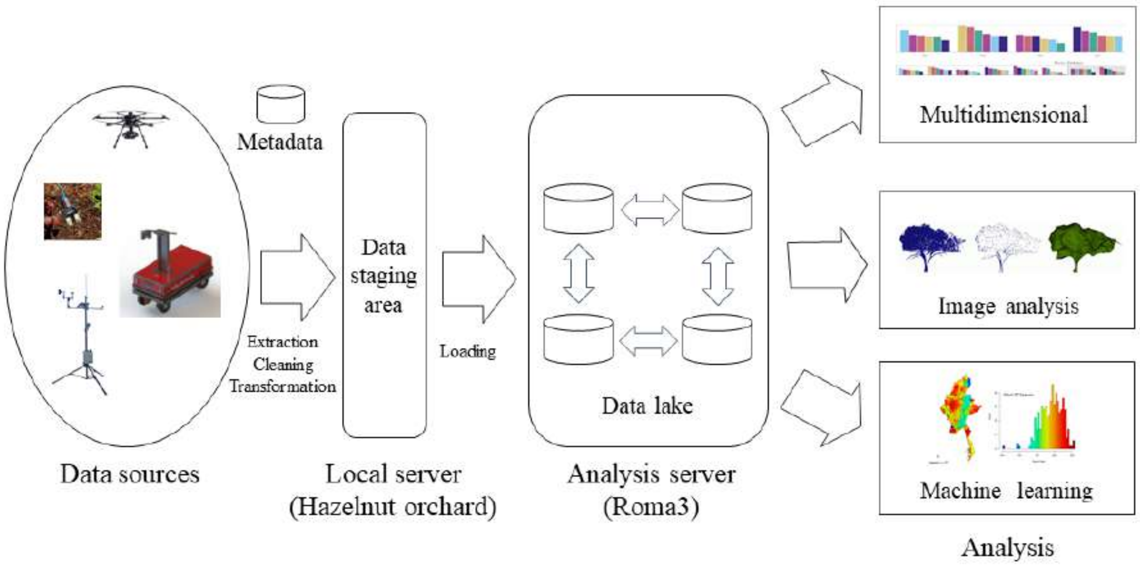

Figure 7. Acquisition data flow schema

As shown in Figure 6 and Figure 7, the data is obtained by the sensors installed on the UAV and UGV platforms during the acquisition missions. In addition, weather station and soil sensors collect data continuously as part of the IoT-based agrometeorological network. All collected data are transferred to the farm server and then transmitted to the central server. The data can be transferred through the Internet connection, if any, or through a manual transport, using specific disks (NAS). The data sent to the central server populate the database to which the analysis algorithms will access. The elaborations are implemented by the processing chains that elaborate the raw data collected and generate final data, which can be accessed by users through the application.

Results

The goal of the system architecture WP was to define a development context suitable for the proposed project and able to support the implementation of the components of the SCADA system.

The Precision Farming application scenario involves many technological challenges including the management of IoT sensors, Big Data, and Analysis for data collecting, processing and presentation. The development of the system allowed to validate the proposed architecture.

In particular, the telemetry management system of the weather station and the soil moisture sensors proved to be very effective. The implementation on the central server has been completed in all its peculiar parts, including the acquisition of streaming and batch data, image processing, database storing and metadata analysis. Everything is controlled and used by the operator through a web user interface that allows an integrated management of the Precision Farming activities.

The development of the system also made it possible to discard or partially implement some of the architectural solutions proposed. For example, we realized the impossibility to have a real-time communication between UAV and SCADA system, because, as reported previously, the UAV control station does not allow any other communication link for safety reason. Furthermore, the choice of installing a local server in the field was overcome as it became clear that it was enough to place an appropriate gateway to manage the telemetry.

A future step will be to bring the functionalities from own central server to the cloud.

System Integration

The whole system integration process has been based on the defined architecture. Each partner of the PANTHEON consortium, with a technological development role, has been assigned one or more subsystems identified in architectural design.

Once the development guidelines and the interconnection interfaces had been defined, each team was able to autonomously develop the modules of the PANTHEON SCADA System.

The strategy followed in integration was to use the best well-tested techniques and solutions, including the "bottom-up" approach in the composition of subsystems, the "publish-subscribe" protocols for data exchange, use of Web API for the deploy of the functionalities into micro-services, and the Web Sockets for the management of data streams.

Figure 8 shows the general scheme of PANTHEON SCADA system. This scheme allows to have a high-level overview.

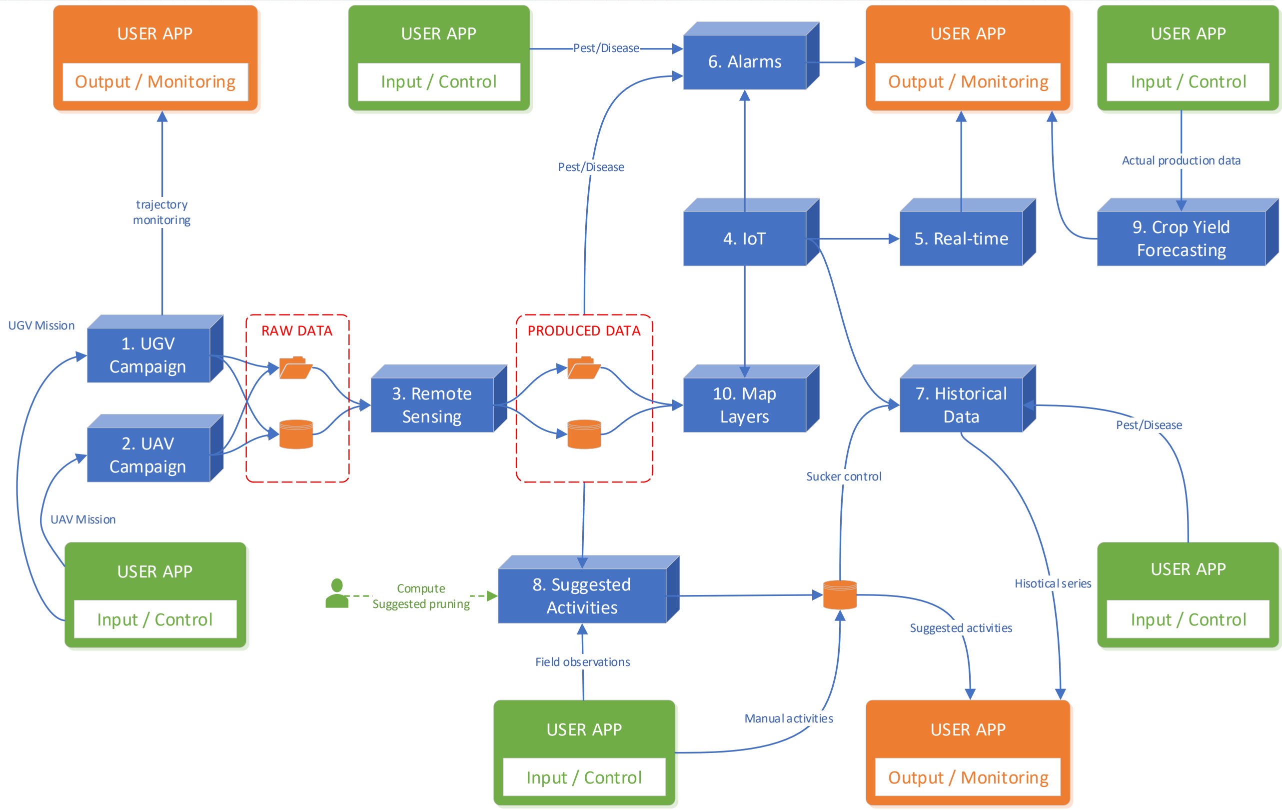

Figure 8. Integration schema overview

In the proposed schema, each subsystem is graphically represented as blue cube. Packages are logically interconnected to show the data processing path. In the diagram, there are green and orange windows that represent the user interface, that is points that allow the input (green) and the output (orange) between the operator and the SCADA system. Please refer to Section 2.3 “Sub-System Design” of Deliverable D6. 2 “SCADA System Integration and Field Validation” [5] for further details on integrated components.

Results

The integration activity made it possible to build the system by composing the blocks, i.e., the components developed by the project partners. The first challenge was the definition of the data exchange interfaces. This task was completed thanks to the collaboration between the units. Particular attention was paid to the development of server-side data management. A micro-service approach was used and dedicated processing flows were developed to handle the data collected from the field. The use of the Node-RED tool proved to be effective for the purpose, and the acquired know-how was spent into the development of other similar projects.

During the integration works, we realized that some parts of the agronomic task management were not fully automatable. This was not an issue as the system allows to support decision making at the same way. On the other hand, the gained experience allows us to think about the development of a product ready solution, minimizing and cutting out the problems encountered.

User Application

Based on the requirements described in Deliverable D3.4 “User Interface” [6], a User Application was implemented. The application should support the agronomists in charge of the orchard for monitoring, decision-making and agronomic interventions.

The User Interface (UI) shows a synoptic view of all the data collected by the remote sensors. In addition, the UI provides the possibility to obtain more detailed information by clicking on the graphical representation of a specific object (e.g., a specific tree). The UI displays the farming operations suggested by the decision-making system once an object has been selected.

The main responsibilities of the web application and the features provides to the users are summarized here:

- Farm management
- Planning of tree data collection missions
  - UAV
  - UGV
- Manual data acquisitions (observations)
- Agronomic operations management
  - Pruning
  - Sucker control
  - Irrigation
  - Pest & Disease
- Monitoring of data collection mission
- Monitoring of the IoT data collection performed by sensor network
- Notifications and warnings of the decision support system
- Analysis of current data
- Analysis of archived data

Based on the widget and interface mockups described in Section 7.3 of Deliverable D3.4 “User Interface” [6], a web application was developed based on a responsive layout to better adapt to the screen size of any device. The web application can be reached at [***https://bartolo.dia.uniroma3.it***](https://bartolo.dia.uniroma3.it) and can be only accessed using credentials.

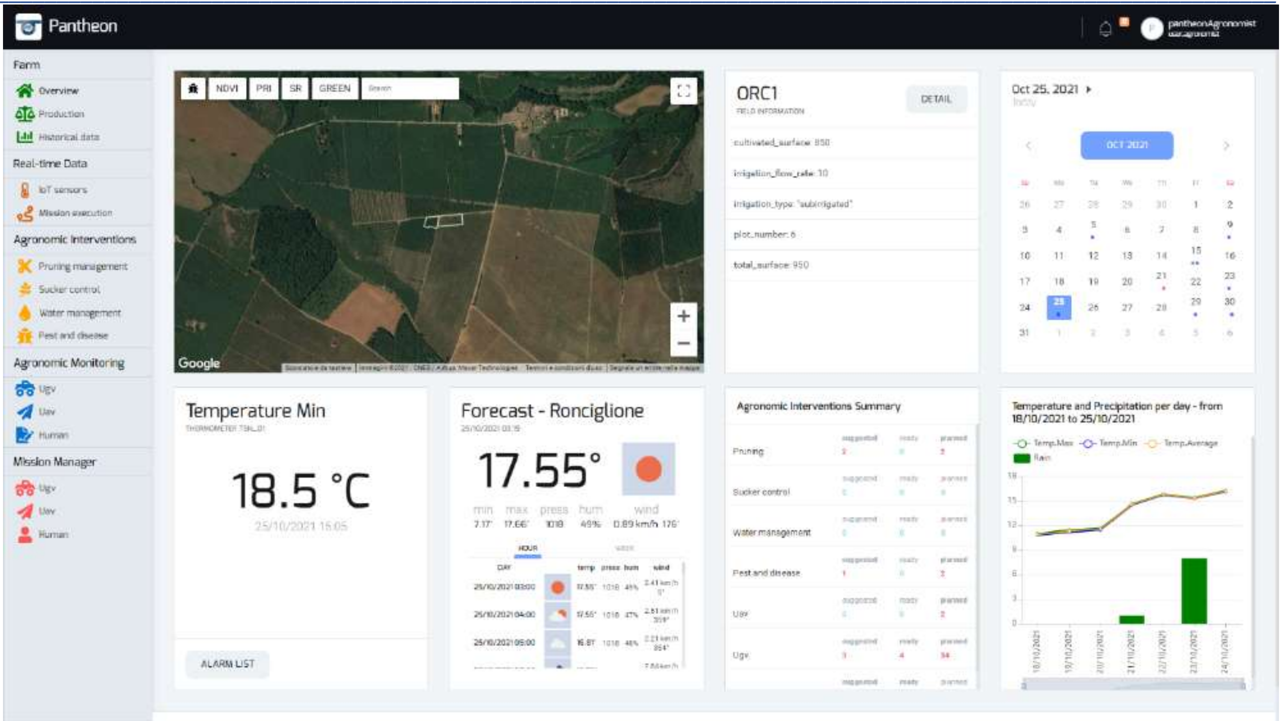

Figure 9. User interface on laptop and large screen

Figure 10. User interface on tablet and medium screen

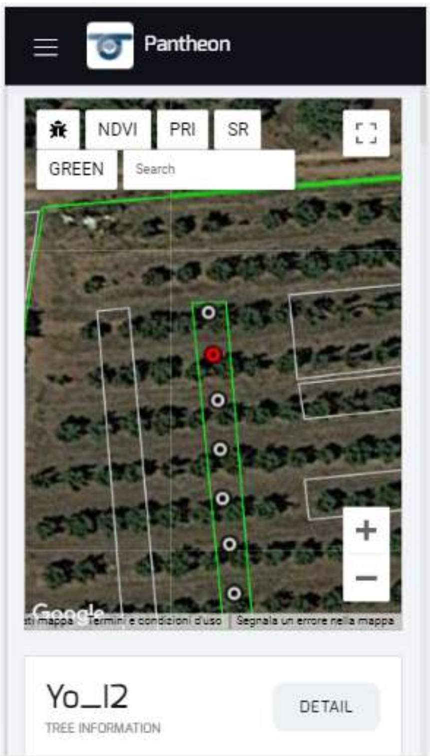

Figure 11. User interface on small screen

For the farm management functions, the Farm section has been prepared which contains in the home page a summary view of the updated data and the interventions to be carried out in the field (Figure 9) and other pages dedicated to the aggregated historical data of the IoT sensors (Figure 12) and production data (Figure 13).

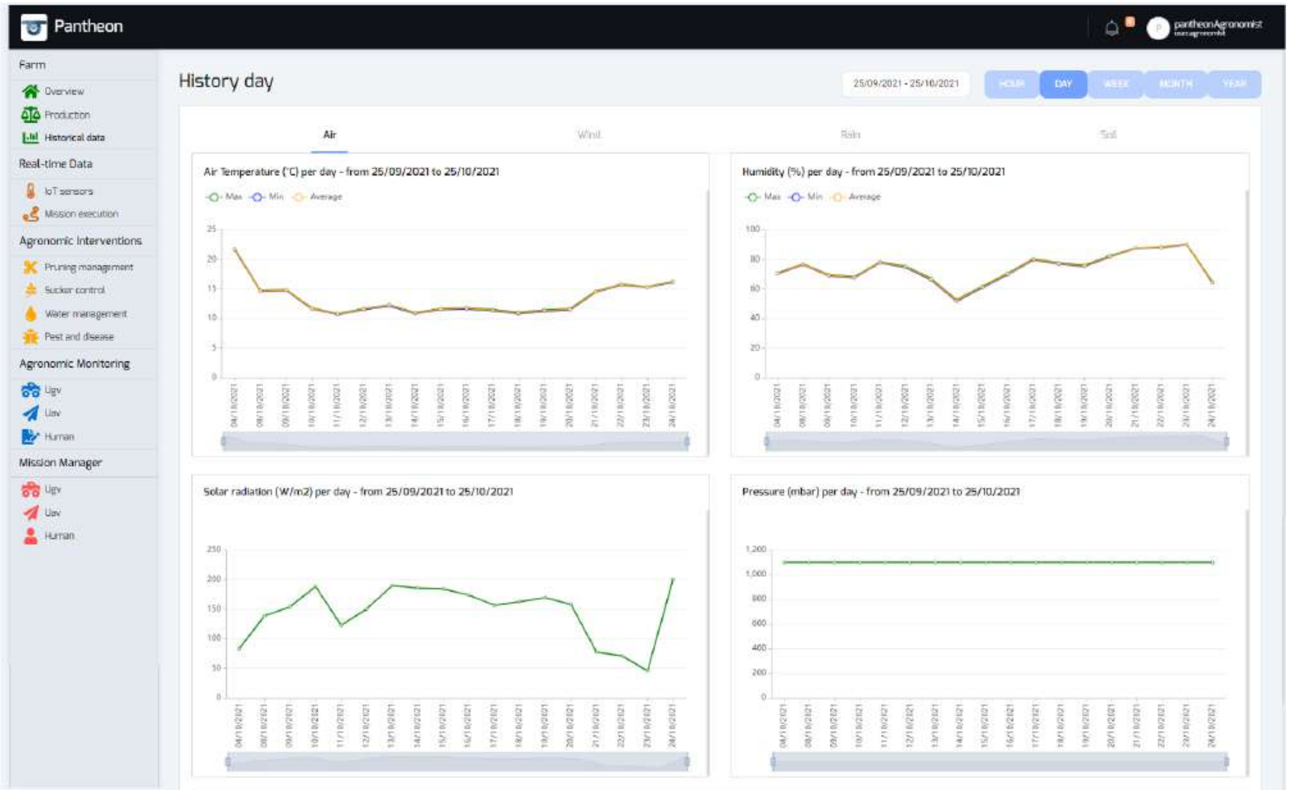

Figure 12. Historical data page

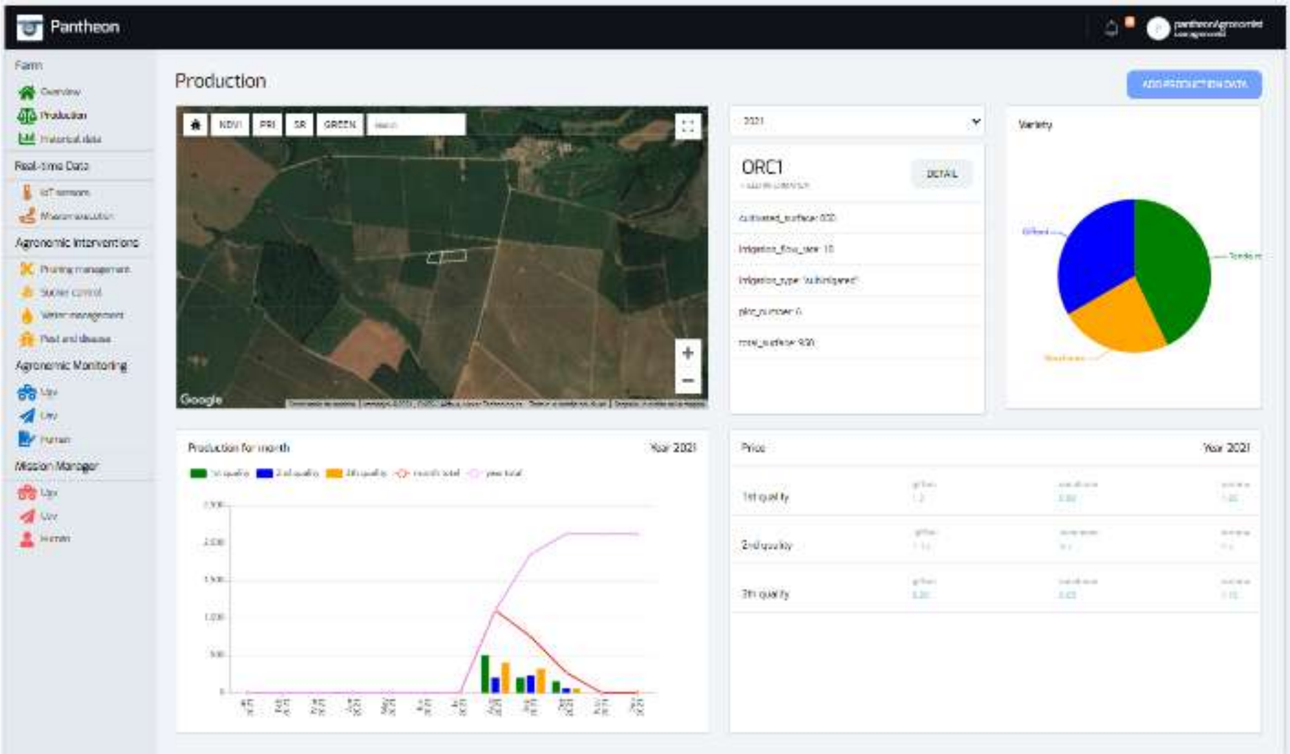

Figure 13. Production data page

Additional production data can also be entered manually (Figure 14) via the interface to integrate the data acquired through the automatic procedures.

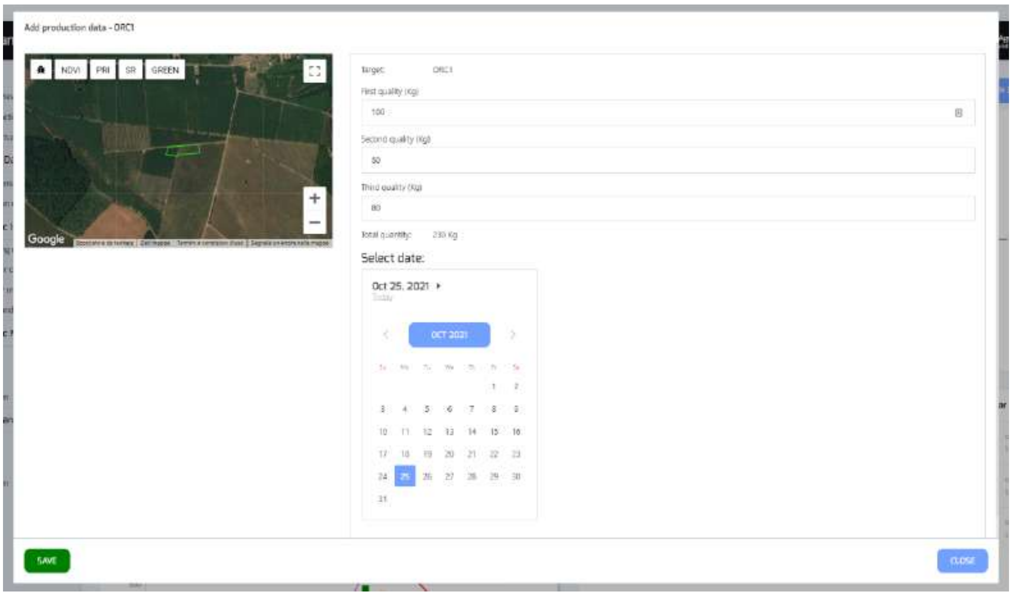

Figure 14. Add production data dialog

For the management of data acquisition and agronomic interventions, the “Agronomic intervention” and “Agronomic monitoring” sections have been prepared.

In the “Agronomic monitoring” section it is possible to insert new automatic monitoring activities with UGV and UAV (Figure 15) and plan them in data acquisition missions (Figure 16).

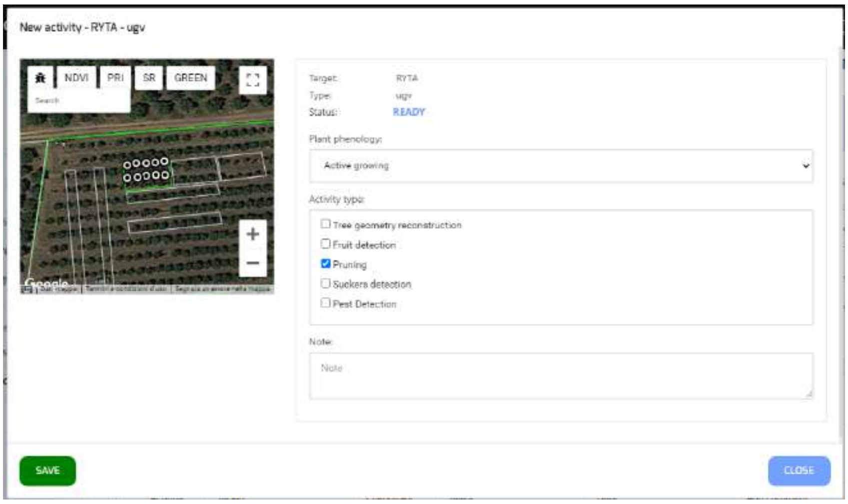

Figure 15. New automatic monitoring activity

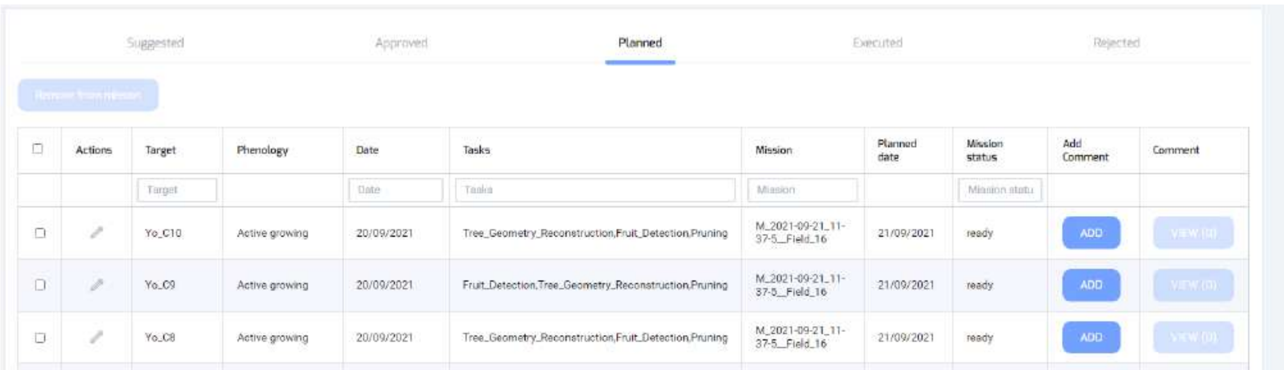

Figure 16. List of activities planned in a mission

It is also possible to insert manual observations through the "Agronomic monitoring – human" section and specifying the details of what has been observed in the field (Figure 17).

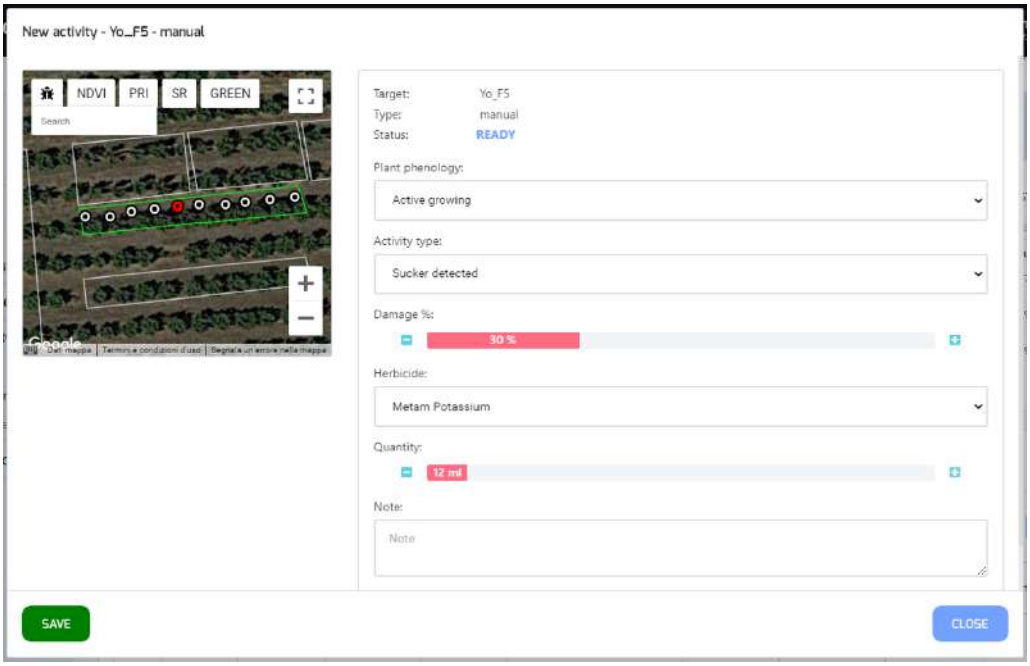

Figure 17. New manual observation activity

In the "Agronomic intervention" section, it is possible to analyze the suggestions elaborated by the decision support system or insert new interventions manually when necessary.

The sections are organized in a similar way, in each of them there is the respective list of activities, grouped according to the following states:

- Suggested: a task suggested by automatic system but not yet analyzed
- Ready: a task approved by user but not yet set and planned for mission
- Planned: tasks that are set in mission and planned depending to mission execution date
- Executed: completed tasks
- Rejected: tasks aborted by user

Figure 18 and Figure 19 show the pruning intervention and the sucker management intervention pages, respectively.

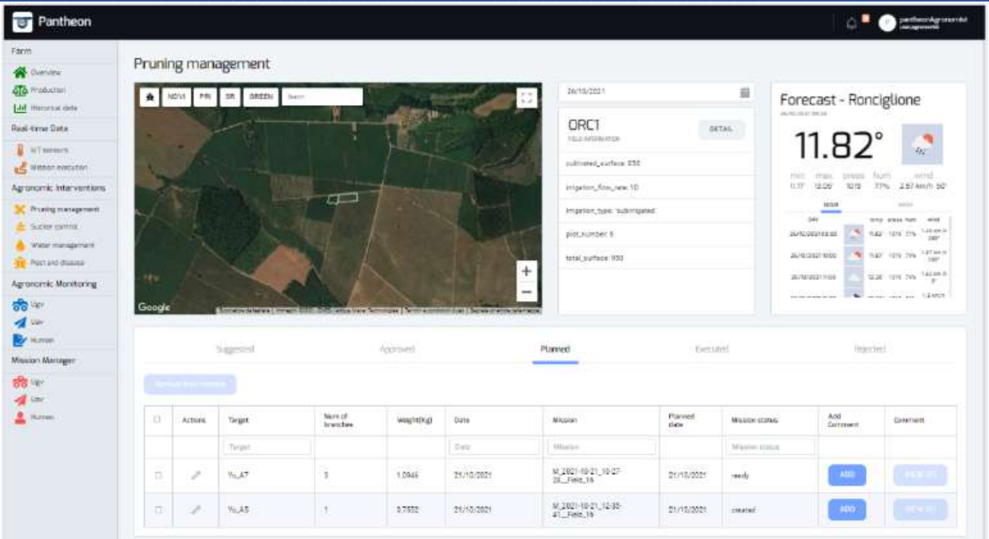

Figure 18. Pruning intervention page

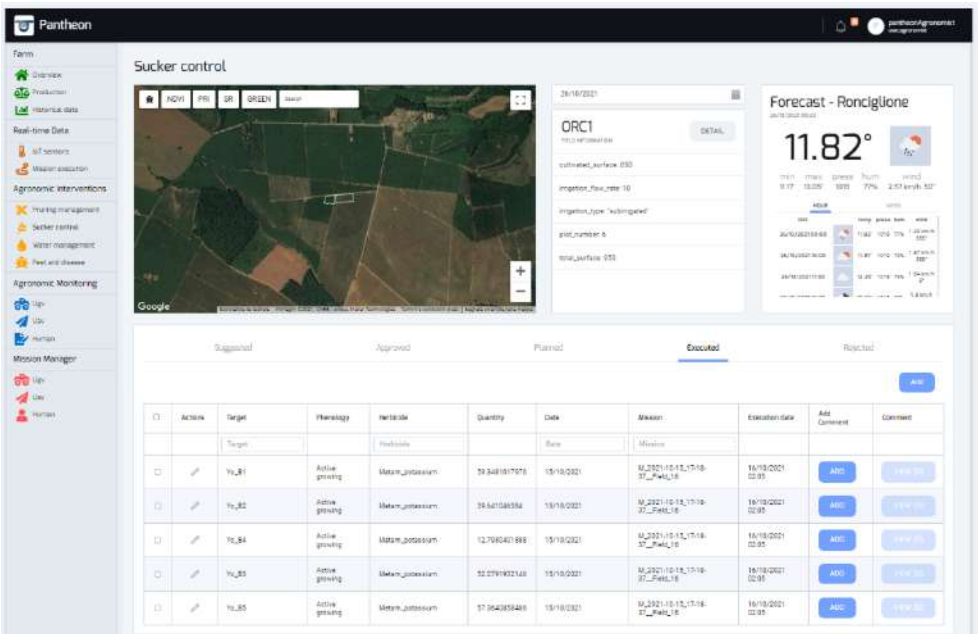

Figure 19. Sucker management intervention page

In the pest and disease page (Figure 20), it is also possible to view on the map the layer reporting the position of the traps in the field and the list with all the acquired data and the count of the detected bugs.

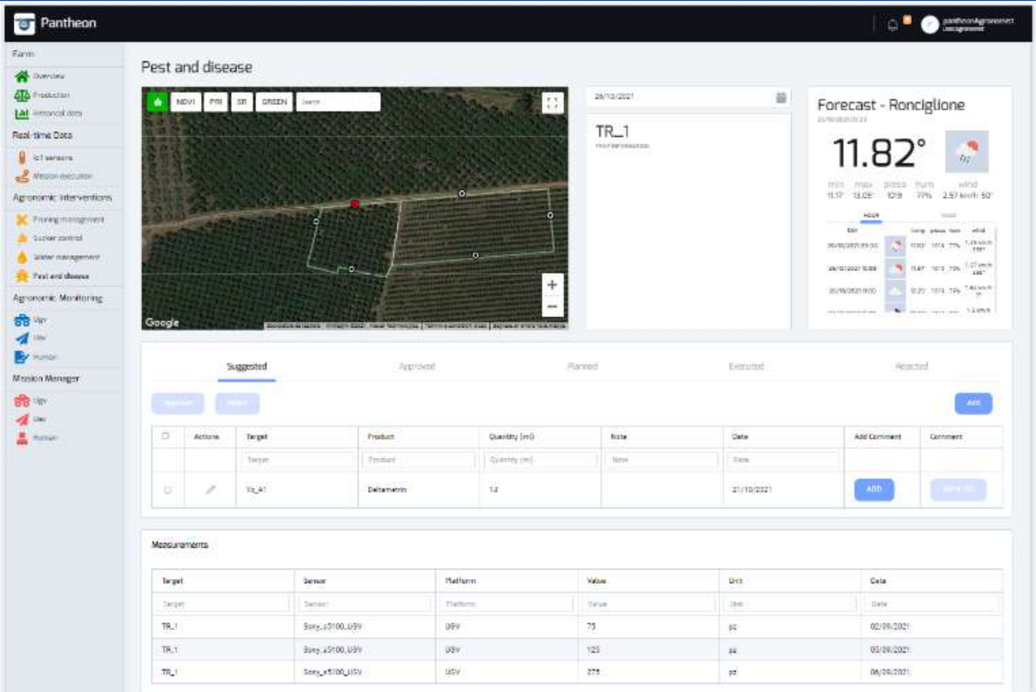

Figure 20. Pest and disease control intervention page

Through these sections, it is possible to manually insert agronomic interventions to be carried out in the field, such as the administration of pesticides (Figure 21) or the pruning of a tree (Figure 22).

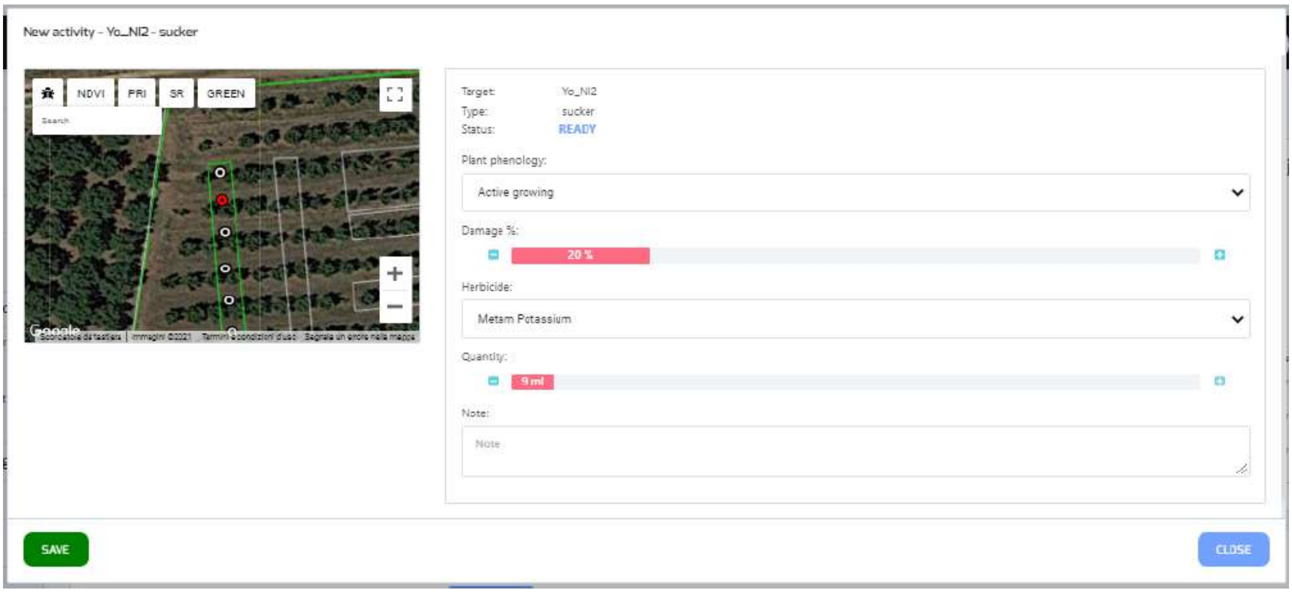

Figure 21. New suckers management activity

In particular, an interactive widget has been created for the pruning activities which, based on the last scan of the chosen tree, allows you to select the branches to be cut, showing in real time what the effect of pruning will be.

This widget is accompanied by the list of branches that will be cut with information on the weight of the branches and the total amount of wood that will be removed.

This view is also available in the detail of the pruning missions so that it can be viewed by the staff who carries out the activity directly by looking at the tree in front of them, in order to facilitate the execution of this activity as much as possible.

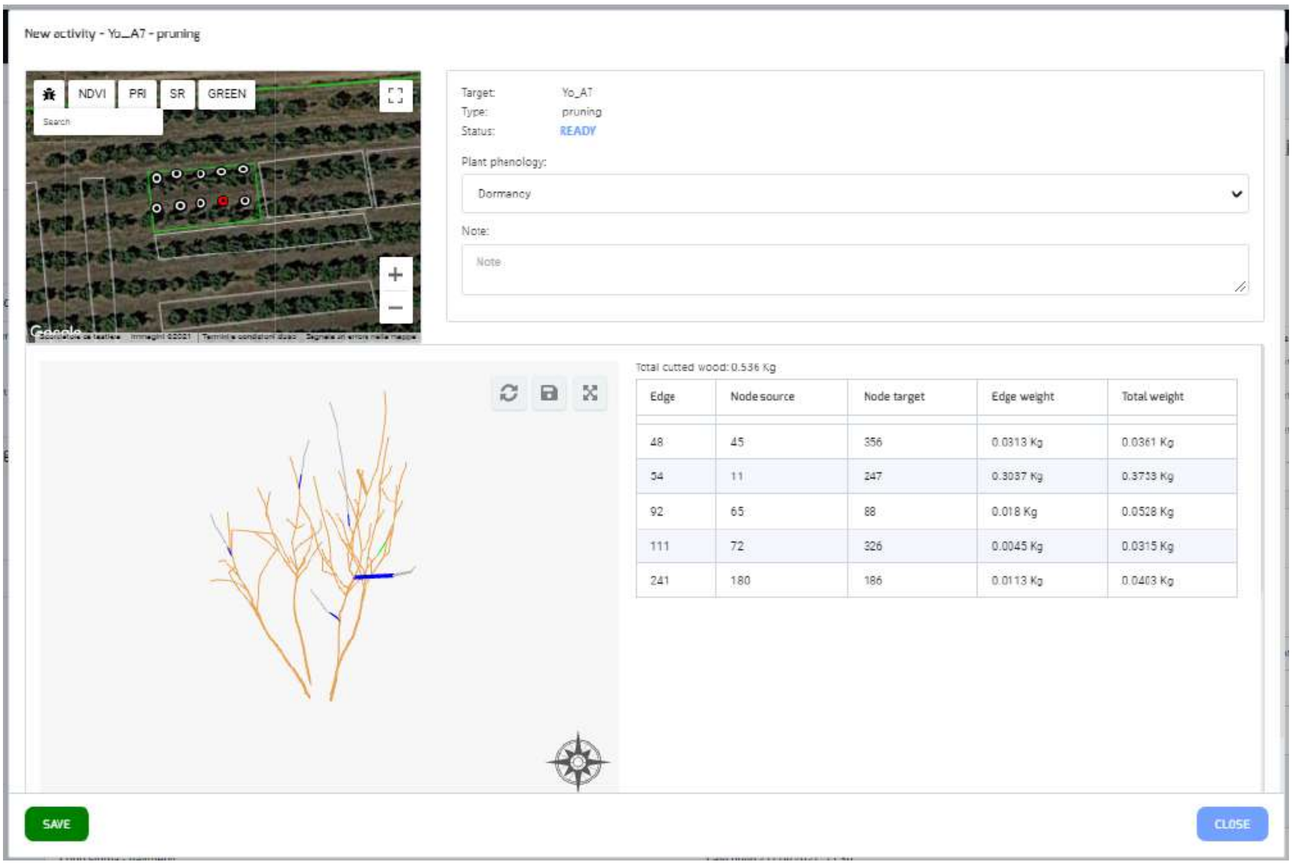

Figure 22. New pruning activity

Through these pages, it is possible to analyze the suggestions created by the decision support system and analyze the details, then approve the valid ones and discard those that are not necessary.

Once this first phase of verification has been carried out, it is then possible to plan the activities manually (Figure 23) or let the farm planning process automatically schedule them.

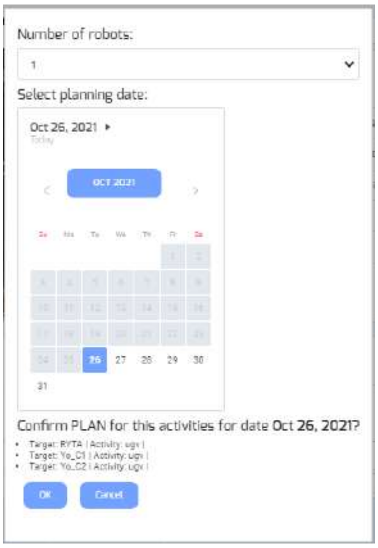

Figure 23. Manual planning activity

The planned activities are grouped into missions based on the type of intervention and the date of execution and can be managed through the “Mission monitoring” section (Figure 24).

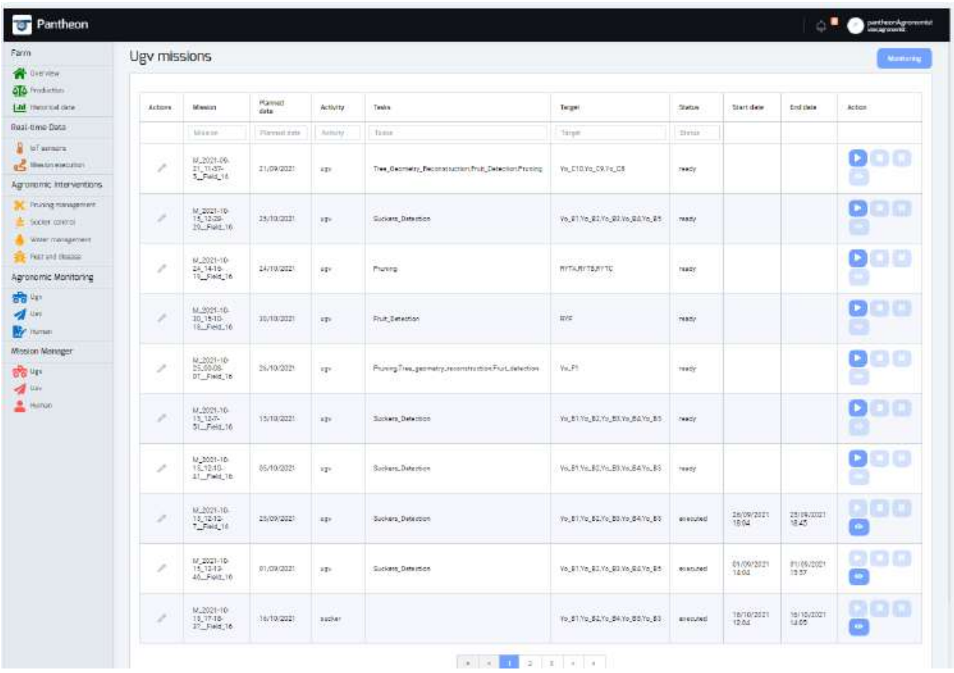

Figure 24. UGV mission page

The missions performed with UGV can be monitored during the execution of the mission and then can be reviewed even after the conclusion of the mission (Figure 25).

Figure 25. Monitoring UGV mission

In the “real time data” section, it is possible to monitor in real-time the weather and ground situation through the data sent by the weather station installed in the field and the sensors on the ground (Figure 26).

In addition, this page shows data calculated based on those acquired, such as hourly evapotranspiration.

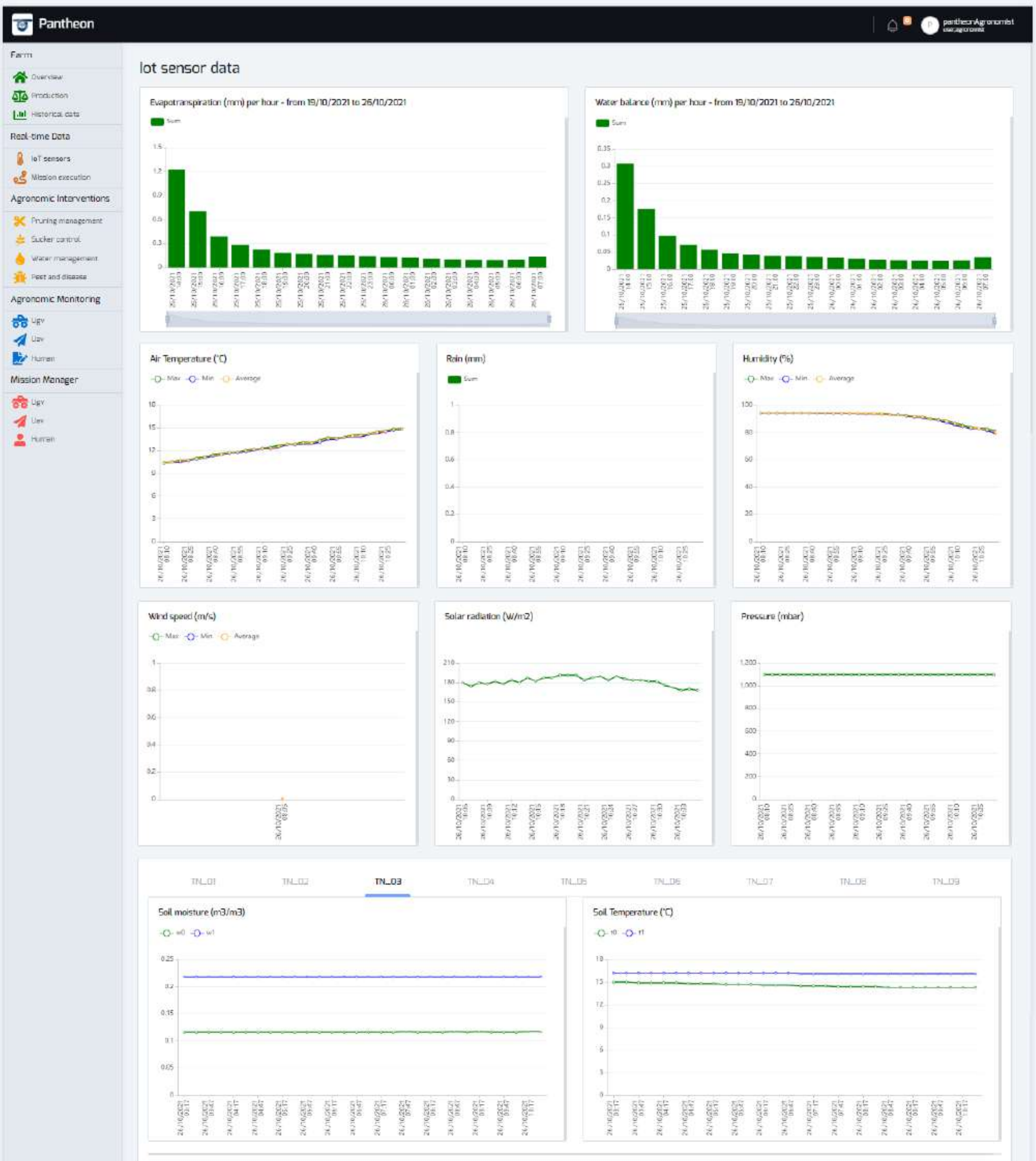

Figure 26. Monitoring real-time IoT page

To notify the user of relevant events concerning the field, the interface has been integrated with the management of notifications from the decision support system.

Active alarms are shown in the header of the interface and remain present until the end of the event (Figure 27).

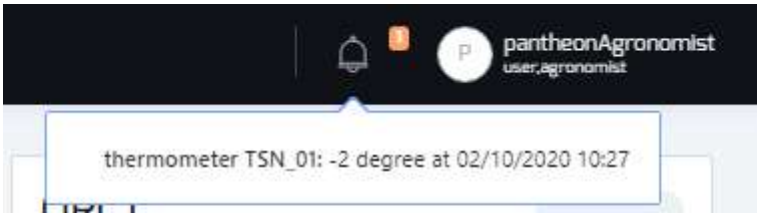

Figure 27. Alarm popup

Moreover, a page is available with the history of all the alarms that have been detected over time (Figure 28).

Alarms list

Created	Sensor	Platform	Type	Active	Closed	Value	Unit	Updated	Count
Created	Sensor	Platform	Type	Active	Closed				
26/04/2021 03:27	thermometer	TSN_01	air_temperature	false	22/04/2021 10:44	-3	degree	26/04/2021 03:27	1
02/10/2020 10:27	thermometer	TSN_01	air_temperature	false		-1	degree	02/10/2020 10:27	1
02/10/2020 10:27	thermometer	TSN_01	air_temperature	true		-2	degree	02/10/2020 10:27	1

Figure 28. Alarms page

In order to analyze the acquired data, both in real time and historical data, a page with the detailed data of each tree has been set up in the interface (Figure 29).

This page shows:

- the position of the tree in the field via the map widget
- the values of the latest measurements performed in the infobox
- the 3D view widget shows the three-dimensional reconstructions of the tree which can be analyzed in detail with zoom and rotations
- with the calendar widget it is also possible to retrieve and view previous data and three-dimensional scans
- the list of all agronomic interventions concerning the tree
- the graphs of the indices acquired through UAV scans

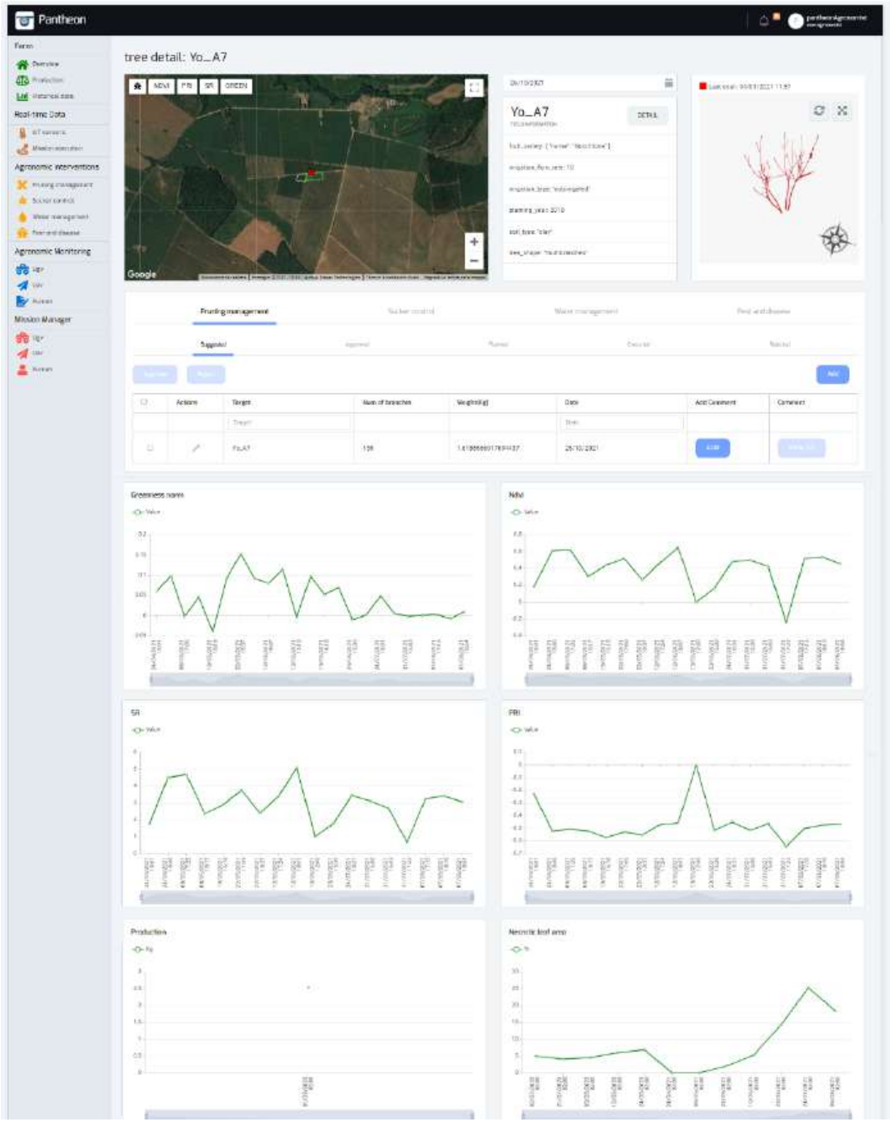

Figure 29. Tree detail page

Results

As required by the Project, an interface for the end user was designed and implemented that would allow to view and analyze the data acquired by the remote devices and sensors and, at the same time, to integrate the data with manually performed measurements.

Through the interface, the acquired data and the widgets that support user decisions, it is possible to evaluate the health of the trees and make decisions on the activities to be undertaken to optimize the productivity and health of each individual tree.

Compared to the original design, it was not possible to integrate the display of the positions of the missions performed via UAV as this data is not communicated by the device, due to the regulations explained above.

In future developments, it is planned to improve the management of user roles by customizing the menus and dedicated sections based on the role, which were currently outside the scope of the prototype.

2 Hazelnut Remote Sensing

In this section the main results of WP4 “Hazelnut Remote Sensing” that have bene experimentally validated are reported. Specifically, the pipelines of virtual tree geometry reconstruction, aerial image processing, pest and disease detection, and fruit detection are discussed.

2.1 Tree Geometry Reconstruction

The tree geometry reconstruction pipeline focuses on the generation of three-dimensional (3D) vector-based hazelnut tree models. We used algorithms such as Iterative Closest Point (ICP) to align independent laser scans of each tree in an orchard to produce consistent point clouds extracted based on the geolocation of an individual tree. Furthermore, algorithms to identify branches, to filter the 3D structure of the multi-stemmed hazelnut trees, and to create 3D tree vector models (Figure 30) have been developed and implemented by adopting existing algorithms, but also by developing new methods where reasonable. These algorithms are further described in Deliverable D4.2 [7]. The 3D models, intended as a base input for the pruning suggestions (Objective 3.1), represent the geometry of a tree as a three-dimensional hierarchical graph. This representation allows for an analysis of the branching topology as well as the estimation of available timber or canopy volume. In addition, the structure has been successfully used for the web-visualization in Task T3.5 “Design and Implementation of the User Interface”.

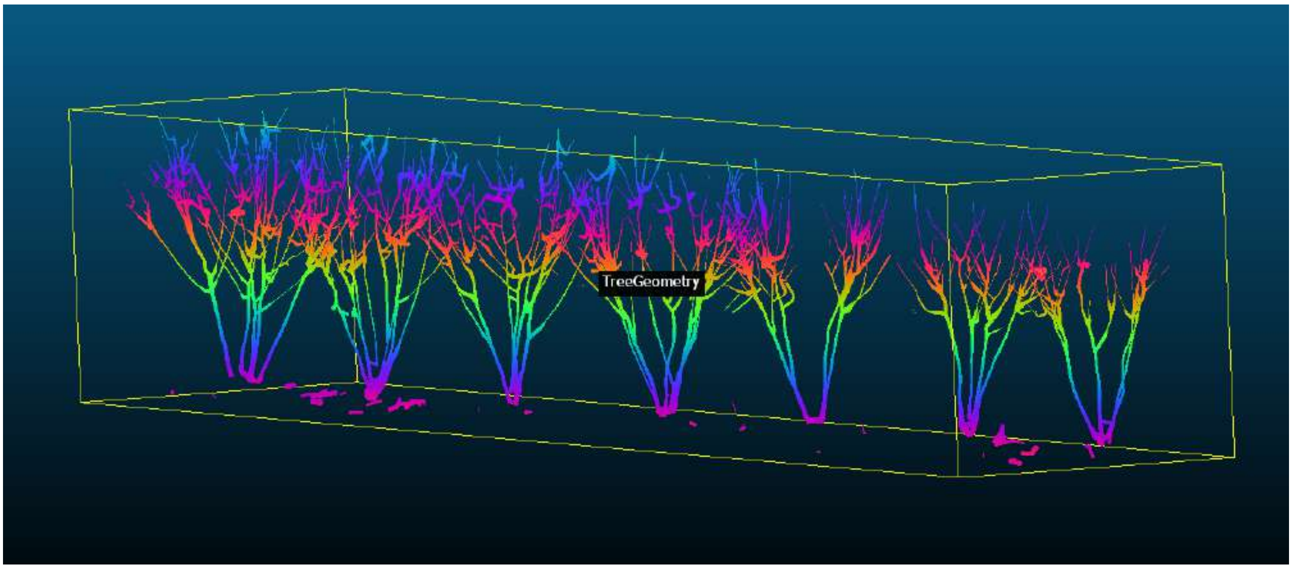

Figure 30. Simplified Vector Based Tree Geometry

2.2 Aerial Image Processing Pipeline

The Aerial Image Processing Pipeline is implemented within the framework of the metashape API of the Agisoft software package. After the image preprocessing, the software optimizes the initial reference position of each image in a process called bundle adjustment. After carefully estimating the observer geometry of each image, the depth, i.e., the location in 3D space, of each individual pixel can be calculated. This results in a sparse point cloud (Figure 31), with each point containing either RGB (Sony camera) spectral (Tetracam

MCAW) or temperature (TEAX) information accompanied by an exact geolocation. Based on these point clouds, a 3D mesh can be calculated and used to compute a georeferenced 2D orthomosaic.

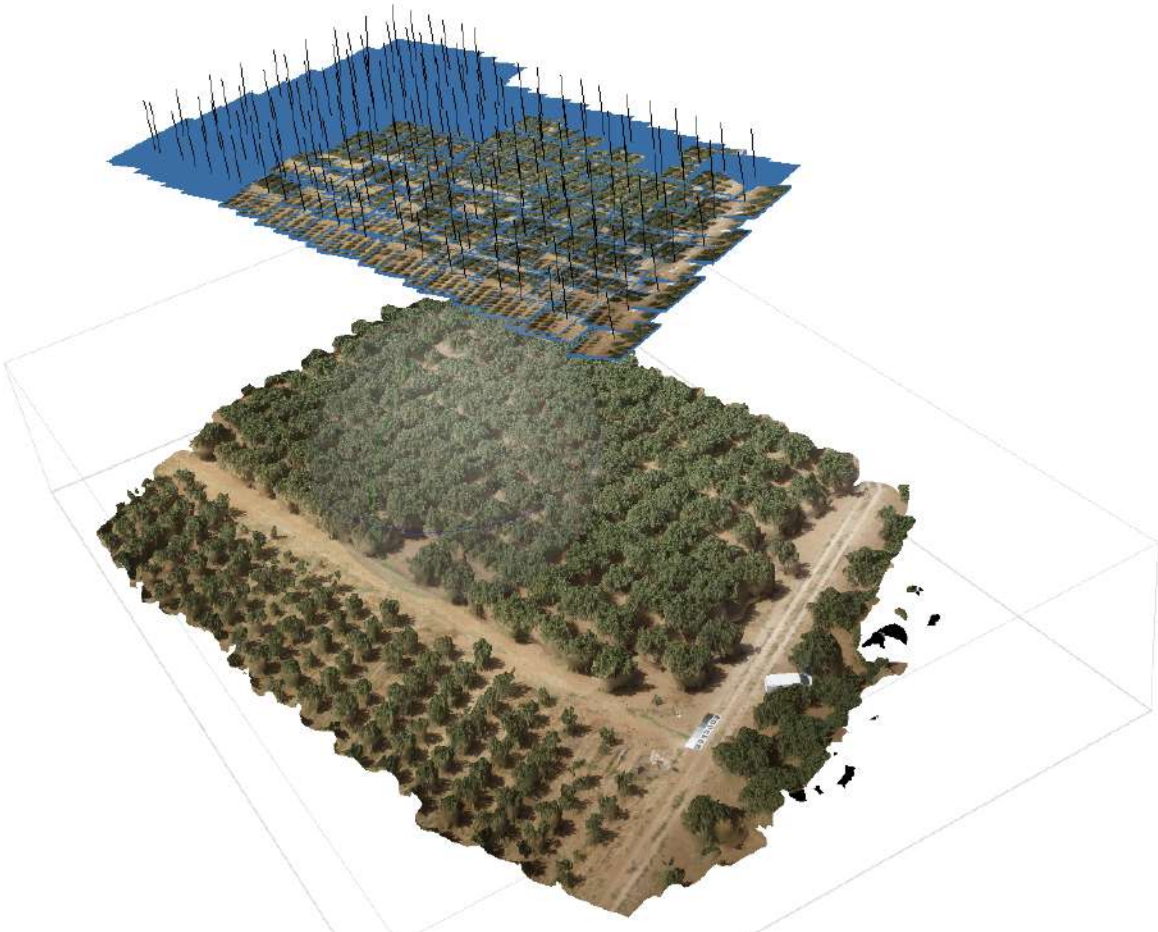

Figure 31. Generating an Orthomosaic based on many UAV images

Based on the extracted orthomosaics, index values such as the Crop Water Stress Index (CWSI) and the Normalized Difference Vegetation Index (NDVI) were computed and correlated to the measured relative water content (Figure 32). Models based on these correlations were established and validated, which can be used to quickly assess local developments based on available new data.

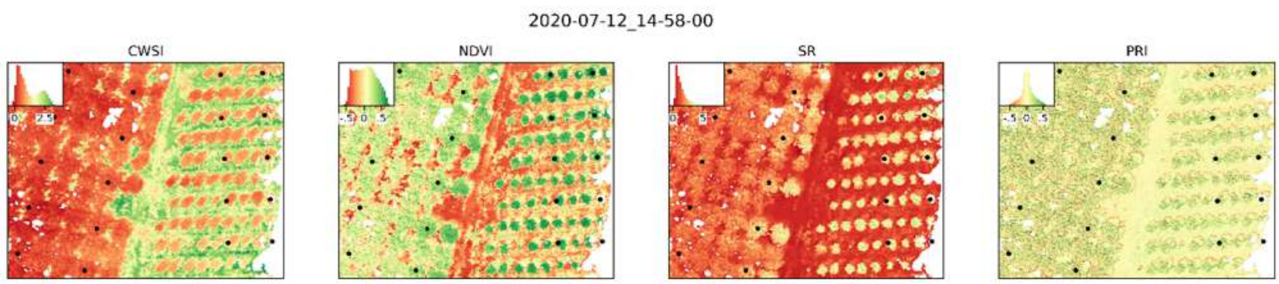

Figure 32: UAV based Index Maps

2.3 Pest and Disease Detection

This objective was meant to provide a reliable architecture for the detection of the main hazelnut pests and diseases. Indeed, this step is mandatory for the development of a novel approach for the monitoring and control of pests and diseases. Notably, the final architecture proposed for pest and disease detection, which is detailed in the following and described by the footage of the accompanying videos, has changed with respect to the approach detailed in Deliverable D4.5 “Pest and disease detection” [9]. This was required since as far as the correlation between various spectral indices and the amount of damaged nuts per tree is concerned, as shown in the Deliverable D4.5 “Pest and disease detection”, none of the spectral indices have shown to be sensitive to the damage in terms of a significant slope nor a meaningful coefficient of determination.

Concerning the true bugs, we proposed an innovative architecture based on the YOLOv4 (You Only Look Once) technology for the early detection of the phytophagous approaching the orchard attracted and collected by pheromone baited traps positioned around the field. As we demonstrated, the YOLO system has been able to identify the true bugs with an accuracy level of 94.5%, and, integrated with standard pest management practices, can reduce human time and effort for dealing with these harmful organisms. Figure 33 depicts examples of the real-time bugs detection capabilities of the proposed YOLO-based system where bounding boxes along with confidence scores are given. The system provides that in April, sticky traps baited with sexual and aggregation pheromone traps must be placed around the orchard. A robotic platform integrated with the described acquisition tool (YOLO system), weekly inspects the traps distributed around the field to intercept the true bugs that move into the hazelnut orchard to begin the feeding phase and causing damages. If the YOLO system detects the presence of true bugs, a human-led monitoring starts, which will determine the presence and numerical consistency of these pests in the field. In addition, the findings obtained within the PANTHEON project, highlighted that the damages caused by these phytophagous are closely associated with the phenological development of the nuts. This suggests that monitoring must involve the presence of true bugs in the field as well as the phenological development of the kernel, to associate the presence of the insect with the damages on the nuts.

Figure 33. Example of real-time bugs prediction capabilities of the proposed YOLO-based architecture

Another entomological problem is represented by the gall mite, Phytoptus avellanae which is an important pest in hazelnut production. The experimentation conducted within the PANTHEON project, proposed a partially automated monitoring system of gall mites, and confirmed the capability of the YOLO technology, integrated in a robotic platform, to identify, with a good level of accuracy (82.5% if the monitoring is conducted at the beginning of spring) the presence of mite induced galls on the plants. Figure 34 depicts examples of the predicted (green) bounding boxes along with confidence scores for the springer (top) and winter (bottom) datasets. Ground truth values are also reported (magenta rectangles).

Figure 34. Example of real-time mite induced galls prediction capabilities of the proposed YOLO-based architecture

The procedure, that is triggered by the automated detection of the presence of galls on plants, let us start a series of human-led activities for the refining of information on the mite population size in the field. In fact, our experiments showed high effectiveness in detecting galls but not healthy buds, which makes it impossible to determine the 20% ratio of galls to total buds which is identified as the threshold for intervention. Our findings, in addition, highlighted that the galls are concentrated on the plant in a belt comprised between 150 and 300 cm from the ground (as shown in Figure 35), and thus it is effective to focus monitoring actions in this area.

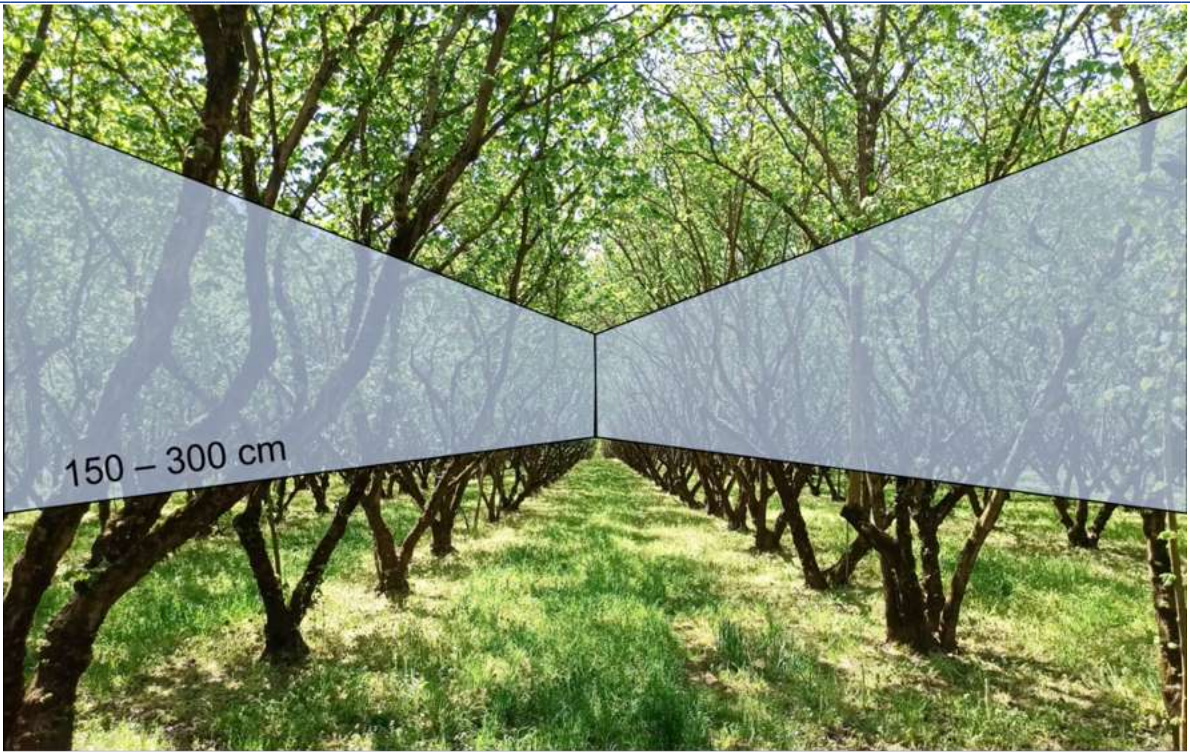

Figure 35. Area indicating where the galls are mostly concentrated according to our experimental findings

As far as disease detection is concerned, the first step concerning the molecular method for detection of M. coryli in plant tissue, both symptomatic and not, has been achieved. Indeed, species-specific primers based on the sequence of the β-tubulin gene were used in a SYBR Green qPCR assay that consistently detected the DNA of the pathogen in naturally infected samples as well as in artificial mixtures of plant and pathogen DNAs with a limit of detection of 10 pg of fungal DNA. The assay and its effectiveness are fully described in a paper entitled “Development of a quantitative PCR assay for the detection of Monostichella coryli, the causal agent of hazelnut anthracnose” [8], submitted for publication in Plant Pathology journal. Then, the influence of temperature on the mycelial growth and conidial germination of the pathogen have also been described in a paper entitled "A novel adaptation of the life tables analysis technique to fungi: modelling germination and mycelium growth rates of Monostichella coryli at different constant temperatures” [9] submitted for publication in Frontiers of Plant Science. The results reported in the paper constitute a preliminary step for the definition of a mathematical model predictive of the disease inception that will be crucial for an effective IPM. Ground truth data about the occurrence of leaf anthracnose were collected during vegetative seasons to be compared with the vegetational indices describing plant health as obtained by processing images acquired by different cameras mounted on by UAV. Finding a correlation between these data should have led to the definition of an automated warning of the onset of disease symptoms and the evolution of plant health condition during the season. However, the data collected were still not sufficient to draw consistent results on remote automated detection of disease occurrence.

Another interesting result obtained in PANTHEON studying fungal diseases of hazelnut is the identification of a new Fusarium species causing nut necrosis. The genome of the fungus was completely sequenced and reconstructed; its comparison with similar genomes deposited in NCBI database provided interesting information about its phylogeny, taxonomy, and biology. Results about this research are reported in the paper “Draft genome sequence of a new Fusarium isolate related to Fusarium tricinctum species complex collected from hazelnut in Central Italy” [10], just accepted for the publication in the Special Issue “Recent advances in hazelnut” of the journal Frontiers in Plant Science.

2.4 Fruit Detection

The main objective of the fruit detection pipeline was to count visible hazelnuts based on the RGB imagery acquired by the ground vehicle (Figure 36). In a first step, hazelnut clusters were marked in an extensive labeling process of over 200 images. These images were then cut up into evenly shaped smaller patches to train a convolution based neural network. After the successful training process, we were able to detect nut clusters automatically on RGB images.

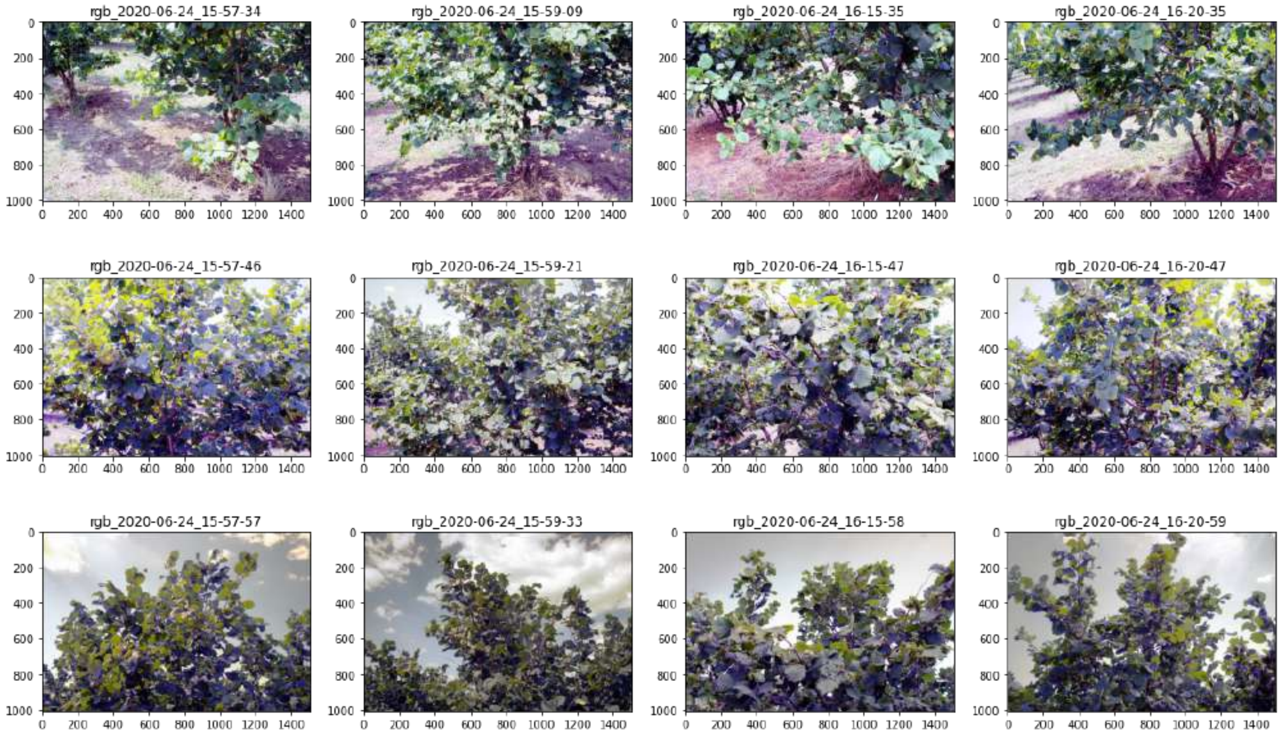

Figure 36. All 12 images looking at a specific Tree

In a next step, we developed a viewer geometry-based algorithm to decide which tree is in focus of which image. In this way, we could assign each detected cluster to a specific tree and add up all visible clusters for each tree. Since only a minority of all clusters on a tree are visible due to leaf occlusion, the automatically detected number naturally underestimates the total number of clusters. We could show that this underestimation was very constant in our sample and could be accounted for with a regression coefficient (Figure 37).

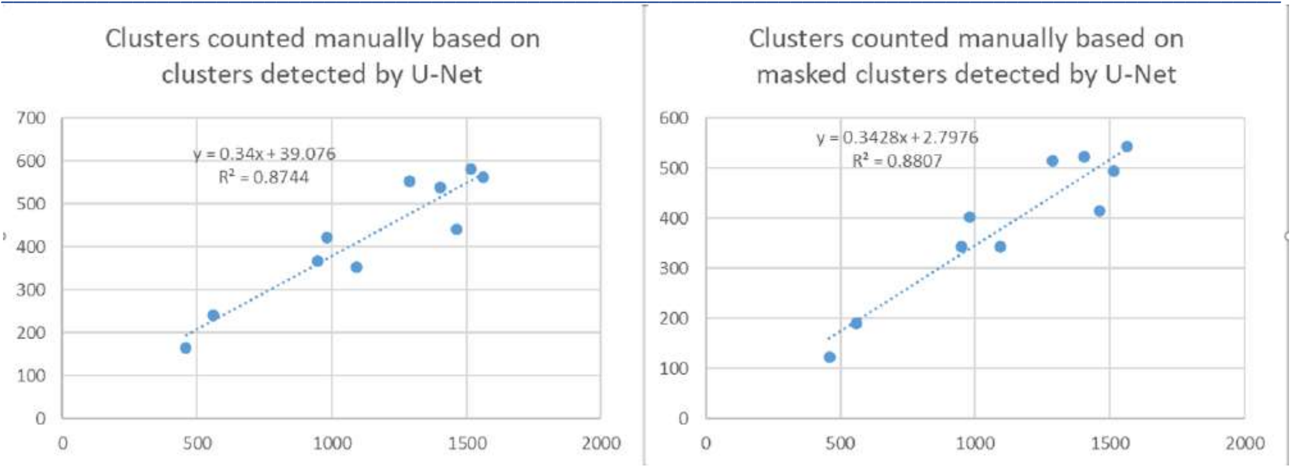

Figure 37. Modeling results for the 10 analyzed Trees of the Fruit Detection Experiment

3 Agronomic Decision Making

In this section the main results of WP5 "Agronomic Decision Making" that have been experimentally validated are reported. Specifically, the protocols for generating pruning suggestions, the management of suckers, fruit monitoring, pest and disease monitoring and control, and yield estimation are discussed.

3.1 Pruning Management Protocol

A plant pruning policy is one of the objectives of the project PANTHEON consisting in the development of an autonomous system capable of suggesting to the user the branches of a tree that should be pruned according to a set of agronomical criteria. The reader is referred to Deliverable D5.3 "Pruning Management Protocol" [13] for further details.

At the beginning of the project a field trial was established to develop protocols and mathematical models able to capture the plant architecture and canopy detection. The objective was to schedule pruning recommendations both to train young plantations and to seasonally prune mature plants. Three different plant training systems have been established in the Field 16 and ten plants were trained at regular bush at four stems (Yo A_n), ten plants at sapling-shape with single trunk (Yo B_n) and ten plants at multi-stemmed bush (Yo C_n).
During the second half of February 2019 all plants were pruned according to the three different chosen shapes, the removed wood was weighted separately from removed suckers, and the pruned plants were periodically photographed and measured during the following growing season. In middle February 2020 the second year of pruning were applied to the trial.
In this case, the interventions were not only aimed at the shaping and pruning of plants, but also at reconstructing the 3D geometry of the plants before and after pruning. These 3D image acquisitions have been very useful for developing the algorithm for pruning.
After a first round of 3D images acquisition using the UGV, carried out in middle February 2020 on un-pruned plants, the team UNITUS pruned all 30 plants of the trial according to the three different chosen shapes, weighed the removed wood per plant and therefore the team UNIROMA3 carried out the second round of UGV acquisitions for reconstructing the geometry of the plants, before and after pruning applications.
The pruned plants were periodically photographed and measured during the growing season 2020. Furthermore, in early August 2020 the pruned plants were 3D scanned again for monitoring the "growth effect" due to the different shape of the plants according to their training.
At the beginning of the second year of the project, we decided to develop together a systematic way to build virtual models of hazelnut trees to facilitate the prototyping and numerical validation of the proposed algorithm. Once the "synthetic tree - case 0" was obtained, it was decided to submit it to the attention of several experts in hazelnut cultivation, to get their opinion on the fidelity reconstruction of the synthetic tree. After the opinion analysis of the interviewed experts, the two teams decided to proceed with the development of the pruning protocol in MATLAB, a numerical computing software developed by MathWorks that allows to manipulate matrices, import and visualize data, and implement algorithms in the homonym programming language, among many things.

The development of the proposed protocol consisted of four phases:
1. Gathering of pruning guidelines from a set of agronomical experts;
2. Development and implementation of a mathematical model able to represent the hazelnut trees in MATLAB;
3. Implementation on the tree model of the pruning guidelines suggested by the agronomical experts;

4. Validation of the protocol on a set of 1000 synthetic trees.

The agronomic guidelines collected in Phase 1 suggested the removal of branches that are responsible for the non-satisfaction of the following criteria:

1. The hazelnut tree can have up to a maximum number of main branches from which it can grow (depending on the training system of the plant);
2. Completely vertical or horizontal branches are not desired;
3. Branches oriented towards the center of the hazelnut are not desired;
4. Branches that may obstruct the movements of the ground robots and tractors are not desired;
5. Short branches in the low-central area of the plant are not desired;
6. Pair of branches growing closely to each other are not desired;
7. Pair of high-altitude branches growing from the same fork should have similar length.

The protocol selects all the branches that do not fit with the detailed criteria and returns the IDs of the branches that should be removed, which will then be visualized on the user's interface along with the overall tree. An estimation of the biomass that would be removed according to the pruning suggestion is also provided.

In order to virtually validate the functionalities of the developed pruning algorithm, we generated 1000 synthetic hazelnut trees and asked agronomical experts to conduct a virtual pruning of branches and shoots, through a properly designed software able to highlight the portion of wood to be cut.

Finally, to validate the algorithm for tree geometry reconstruction and pruning guidance on real trees, starting in January 2021, two different validation approaches were carried out.
The first activity concerned the "test plants" already used in February 2020 (A6, A7, A8; B5, B6, B7; C7, C9 C10) through the application of the manual pruning protocol previously described, with acquisition of 3D scanning to be done before and after winter pruning, using the properly equipped UGV (Figure 38). This activity was aimed at further validating the protocol to the type of cuts to be recommended, which can be different from year to year, depending on the vegetative development of the plants.

Figure 38. UGV acquiring data for the tree geometry reconstruction which enables the generation of the pruning suggestions

The second activity was exclusively aimed at validating the pruning protocol through a preliminary 3D scanning with UGV of the other plants of the trial, after eliminating the catkins, to obtain the automated indications of which portions of plants to cut, according to the different plant shapes. Once the information was acquired, agronomical experts manually applied the cuts proposed by the pruning algorithm and once the pruning has been carried out, they agronomical validated the post-pruning architecture of the treated plants according to the agronomical guidelines available in literature for all three adopted shaping. Figure 39 shows the validation of the pruning protocol on the field, where in the bottom right side the virtual tree and the pruning suggestions are shown.

Figure 39. The agronomic expert follows the pruning suggestions made by the automated pruning protocol

3.2 Suckers' Management Control

One of the key objectives of the project PANTHEON consists in the development of an autonomous system able to decide whether a plant needs a suckers' treatment or not. This objective has been achieved with the implementation of an autonomous architecture that is first able to detect the presence of the suckers in a plant and then, if needed, also treat them accordingly. The reader is referred to Deliverable D5.2 "Suckers' Management Control" [11] for further details.

Briefly, the suckering control solution of PANTHEON is composed of two steps. In the first step, the characterization and estimation of sucker canopy dimensions of every plant was carried out. In the second place, tailor-made treatments were computed and applied, to allow the application of different rates of herbicide to each tree. This innovative solution may significantly reduce herbicide volumes and enhance plant health conditions.

In suckers' management control, the field application of the herbicide was performed using SHERPA HL robotic platform R-B which is equipped with an RGBD sensor camera for the detection of the suckers, a tank containing the solution of herbicide, a sprayer along with an electrical driven pump and pan-tilt motion capabilities to steer it. In this context, the objective, besides the detection of what plants to treat, included the way the treatment was administrated such as the position of the UGV, the nozzle type, the application time of the herbicide, the distance at which the UGV should be located and the position of the sprayer with respect to the tree. Additionally, we studied how this distribution varies given different nozzles.

Through weekly observations in both adult (Fields 18 and 21) and young plants (Field 16), the growth and development of suckers were monitored in 2018 at the PANTHEON experimental farm with the aim to develop the best strategies for estimating the suckers characteristics of each plant. The most representative characteristics for the purpose of effective application and reduction of use of the suckering herbicide were:

1. the volume and the surface area of the suckers' canopy at the base of the stump or trunk;
2. the spectral response of the suckers themselves.

These characteristics were then used to model the suckers herbicide estimation protocol that is part of the suckers management architecture. Specifically, the processing pipeline for the automatic management of the suckers is structured as follows.

Once that the robot reaches the area of interest in the orchard, the following operations are performed. First, the RBGD camera mounted on the robot is activated and its output, i.e., the RGB color image and the depth map, are fed into a YOLO-based neural network that detects the presence of the suckers. Next, this information is used to segment both the RGB color image and the depth map and it is then fed to another component which reconstructs a 3D mesh model of the segmented environment. When the robot has visited all the target trees, a filtering procedure is applied to the reconstructed environment to properly extract and isolate the suckers from the 3D mesh. Multiple 3D meshes are generated (exactly one per sucker, i.e., per tree) and an estimation of the canopy area for each of them is computed exploiting the polygon faces of the 3D meshes. The estimated area is then used to compute the amount of herbicide that is required for the suckers' treatment. Figure 40 shows the SHERPA HL robotic platform R-B on the field while it is virtually reconstructing the suckers of the orchard.

Figure 40. Real-time suckers' reconstruction conducted by the SHERPA HL R-B

Next, the robot navigates to the trees which have been recognized as in need for suckers’ treatment and apply the computed amount of herbicide. Figure 41 depicts the application of the herbicide to a suckers with surface area equal to 2.349m^2.

Figure 41. Application of the herbicide after the canopy area of the sucker has been estimated

The developed management architecture is able to decide whether a plant needs suckers treatment or not and can compute the specific amount of herbicide to be sprayed based on the indicators defined in Objective 2.1 of the DoA.

The following activities have been carried out for the validation of the developed architecture:

1. Automated and manual quantification of the amount of herbicide to be sprayed in the selected trees;
2. Automated and manual herbicide application to the trees selected as in need of treatment;
3. Monitoring of the changes in terms of effectiveness for sucker drying between the two approaches of application (traditional vs automated);
4. Monitoring of the interval between two consecutive treatments (in case of suckers regrowth) and if and how this is influenced by the two approaches.

Notably, the final suckers management architecture detailed above and showed in the video attached with this document has changed with respect to the one detailed in Deliverable D5.2 “Suckers' Management Control” [11]. In particular, we developed a novel architecture focused on the estimation of the canopy area of the suckers, rather than on the estimation of their volume. Experimental campaigns conducted in the 2021 summer season proved how the novel canopy-based architecture was more effective in correctly estimating the amount of herbicide. For this reason, the processing pipeline has been updated and it is now able to compute the amount of herbicide based on an estimation of the surface area of the canopy of the suckers. The improved architecture has been detailed in the recently submitted work [12].

3.3 Pest and Disease Monitoring and Control

The automated management of pests and diseases is one of the objectives of the project PANTHEON consisting in the development of automated strategies for the management of the main hazelnut pests and diseases. More details are presented in the Deliverable D5.4 "Pests and diseases monitoring and control" [14].

As far as pest monitoring and control is concerned, a partially automated system for the management of both true bugs and gall mite has been developed. Regarding the true bugs system, which is represented in Figure 42, it is based on the following 3 steps:

i. Sticky traps baited with sexual and aggregative pheromone traps, commercially available, must be placed around the hazelnut plantation in April, in concomitance with the vegetative restart. After positioning, a robotic platform integrated with the described YOLO system must inspect, on a weekly basis, the traps distributed around the field.

ii. If the system detects on the traps the presence of true bugs, a human-led monitoring (frappage) must start, which will determine, on a weekly basis, the presence and numerical consistency of true bugs in the field. At the same time, a human-led monitoring must be conducted to determine the susceptibility of the nut to the damage activity of true bugs.

iii. If the threshold is overcome, chemical treatment must be applied, depending on the production system that the farmer has decided to adopt (organic, mandatory IPM, voluntary IPM). In the Latium region, where the experimentation has been conducted, 2 specimens/plant collected weekly on 10 plants is the threshold above which, damages occur.

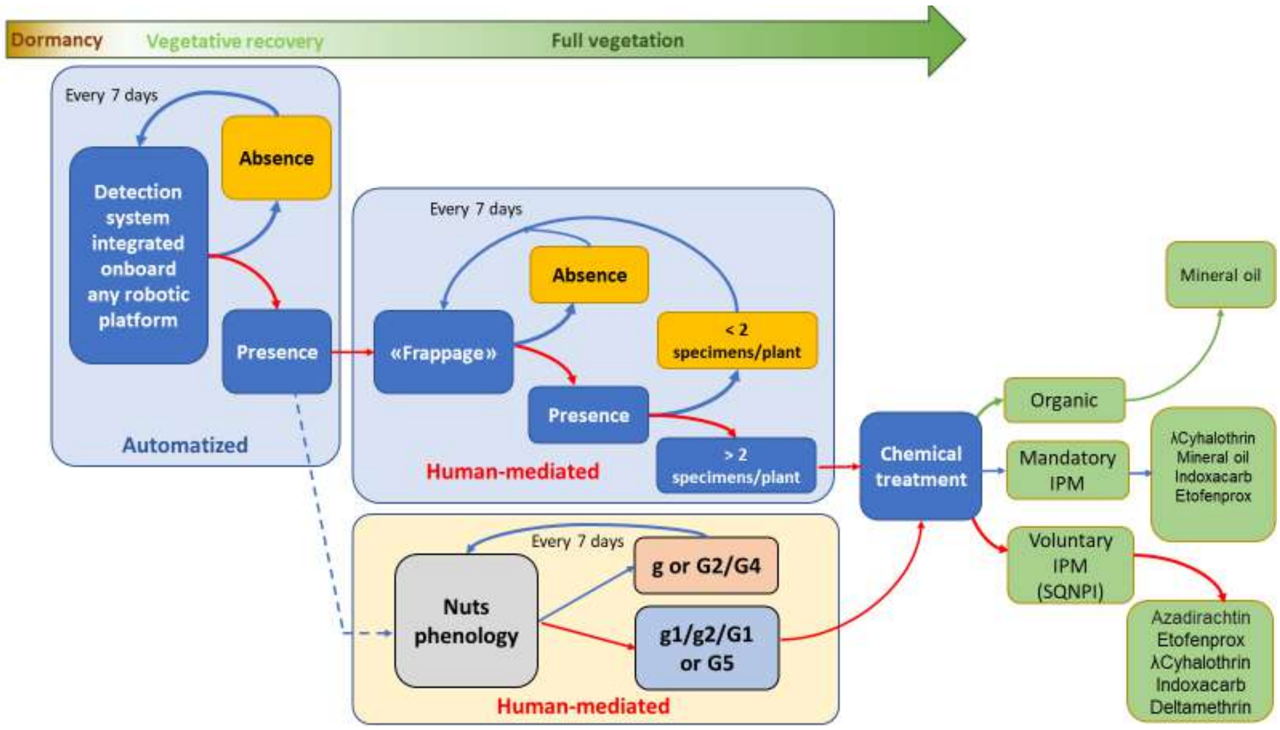

Figure 42. The flow chart represents the new guidelines for the management of true bugs in Latium Region Italy, integrating an automatized detection with usual human practices

Regarding the gall-mite management, which is represented in the flowchart in Figure 43, the partially automated system provides:

i. At the end of winter/beginning of spring, a robotic platform integrated with the YOLO technology must inspect randomly selected plants, in a section comprised between 150 and 300 cm from the ground, to determine the presence of galls induced by the mite.

ii. If the presence of galls is highlighted, it triggers a series of human-led activities for the refining of information on the mite population size in the field. In fact, the high effectiveness in detecting galls but not healthy buds make it impossible to determine the 20% ratio of galls to total buds identified as the threshold for intervention.

iii. If monitoring highlights that the threshold is reached, a chemical treatment must be applied in the zone between 150 and 300 cm above the ground, during the mite migration phase. This normally occurs in April/May. The selection of the active ingredient is ruled by European, national, and regional regulations and is based on the phytosanitary management that the farmer has decided to apply (organic, mandatory IPM or voluntary IPM).

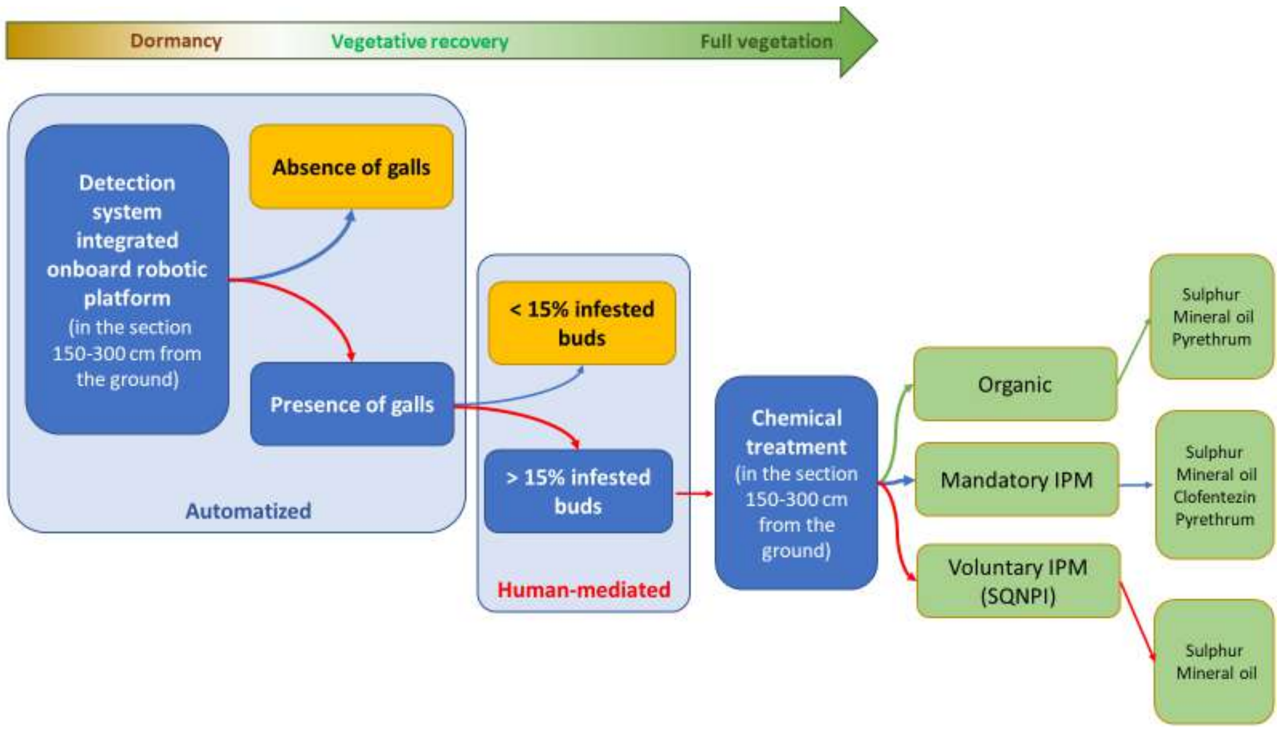

Figure 43. The flow chart represents the new guidelines for the management of gall-mite in Latium Region, Italy, that integrates usual human practices with an automatized detection of the pest

Regarding the disease management, it should be noticed that nowadays according to the state of the art, the hazelnut anthracnose can be controlled only by preventive scheduled treatments with copper in both IPM and organic farming in Latium region. However, these treatments are scheduled regardless of the real occurrence of the disease or not. In the project, we attempted to organize a decisional workflow based on both human-mediated and automated information, aimed to determine the timing and significance of disease presence, and consequently providing a warning alert indicating that phytosanitary treatments are required and their best timing. Specifically, this decisional workflow is based on the following 3 steps:

i. evaluation of the presence of the pathogen in dormant buds (%), assessed by species-specific qPCR (HUMAN-MEDIATED) on a sample of 20 buds per plants (10 plants/ha). If the pathogen is present, a visual evaluation of bud rot incidence should be carried out by trained technicians. Even if a clear correlation between the bud rot incidence and the incidence of the disease during the season wasn't still defined, a threshold of 20% of damaged buds seems to be plausible.

ii. Model prediction of the evolution of the disease in field according to meteorological data (AUTOMATIZED). When the threshold above is exceeded, a prediction model should be run to forecast the growth of the fungus in plant tissue, its sporulation the spread of the spores in the environment and the germination of spores (conidia). This model is at its first steps of definition, with details only about the influence of temperature on mycelial growth (T_M, T_L and T_{OPT}) and on conidial germination.

iii. Early assessment of plant disease on canopy (AUTOMATIZED). This step implies the assessment of anthracnose incidence from vegetational indices acquired from UAV and it should flank the indications provided by the predictive model. When a disease index threshold (to be defined) is exceeded, the system suggests the execution of a phytosanitary treatment to the farmer. As things currently stand, NDVI and SR (Simple Ratio Index) are the most promising vegetational indices, but further experiments are needed to corroborate the results.

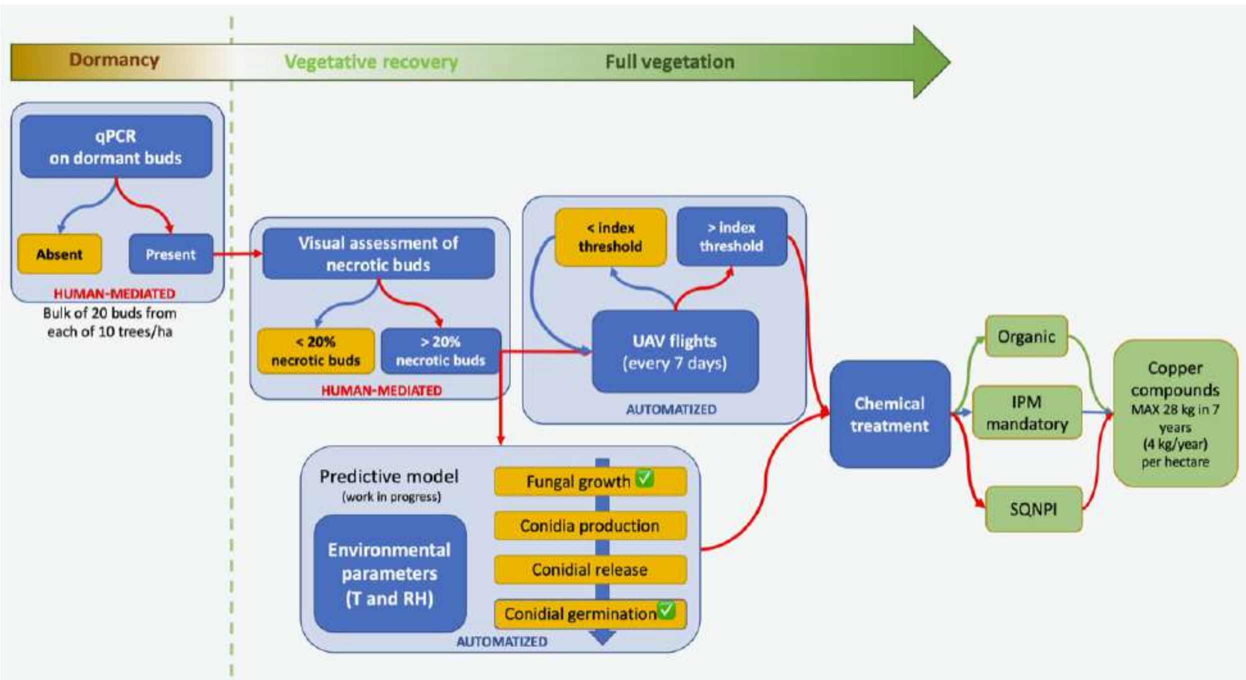

Figure 44. The flow chart represents the concept guidelines for the management of anthracnose, integrating human mediated and automatized protocols. Treatments are in agreements with regulation in Latium Region, Italy.

The basic concept for the implementation of future decision support system for integrated Pest Management of this pathogen is represented in Figure 44. The chemical treatments for the control of these fungal pathogen are subject to European, National and Regional regulations and are also dependent on the production system chosen by the farmer (organic, mandatory IPM, voluntary IPM).

3.4 Fruit Development and Production Monitoring

Fruit development and production monitoring is one of the objectives of the project PANTHEON consisting in the development of a novel method for a reliable estimation of the yield per tree.

Notably, a fundamental step for the design of a prediction approach is the collection of high-quality ground truth data. In this regard, to find the best times to perform cluster and nut counts in relation to their development, maturation and early dropping, nut and kernel development monitoring was conducted during the growing season 2018 in mature trees selected in the fields 18 and 21 on cultivar 'Tonda Gentile Romana'. The observations were done weekly starting to the bud break stage until the harvest time. During the growing season 2019, an accurate manual counting of clusters and nuts was carried out in the selected plants in the field 16. This counting was performed by two-person team of agronomical experts, in which one person accurately counted the clusters per branch and one person recorded the data. This prevented omitting some clusters hidden in the canopy during counting. In the same growing season, only the manual harvest of the nuts was carried out in the field 18 on selected mature plants since the manual count in adult hazelnut shrubs is non-trivial and very time-consuming. On the contrary, manual counting of clusters compared to nuts is easier as they are larger and of light-green color. Thus, during the growing season 2020, this alternative approach was tried also for mature plants. The morphological traits of the clusters, such as color and size, can also be an advantage for their detection through properly equipped UAVs and UGVs, even if clusters are often covered by leaves and are not only placed in the outer portions of the plant crown. Regarding the young plants, during the growing season 2019, the manual counting of clusters and nuts per plant in field 16 took place in mid-June and late-August, while the manual harvest occurred in mid-September. Counts taken at different times during the growing season were thus compared for determining the best period to estimate yield per plant, also considering the early drop of defected nuts that do not reach the full ripeness.

The approach followed during the first year of the trial, even if tested on the young plants only, was highly time-consuming. However, this allowed to verify the reliability of cluster counting only, which should be carried out after the early drop of defective nuts (late July - early August depending by the cultivar and environment). During the growing season 2020 (second year of the trial), the manual count of the clusters took place in early July, middle August, and early September, on the selected plants in field 16. In June and August, the total number of nuts per plant was estimated from the average number of hazelnuts per cluster, while at harvest time, total number of nuts per plant was also determined through their real counting. Nevertheless, as expected, the average number of nuts per cluster was very similar to that observed in 2019. The manual counting of clusters per plant during 2020 was also supported by 3D acquisitions conducted using the UGV, during the same days that manual counts were conducted. As observed in the previous year, the number of clusters and nuts was very similar to that observed in the previous seasonal count, confirming that production losses during this period of the growing season do not highly affect the final yield. As far as the mature plants (Field 18 - cv 'Tonda Gentile Romana') are concerned, during the growing season 2020 some representative branches of the selected plants were labelled and, similarly to the young plants, 30 clusters per branch were counted for their nuts content in early August, to determine the average number of nuts per cluster. The average number of nuts per cluster revealed for the cultivar 'Tonda Gentile Romana' was slightly higher when compared to 'Nocchione' with average values of 2.8 nuts per cluster.

Regarding 2021, this growing season was not very suitable for replicating field observations, as the seasonal production of the plants was almost entirely compromised by extensive cold damages to plants caused by late spring frosts (- 8°C degrees in early April 2021). For this reason, additional five plants were added to the young trial in order to increase the chances for validation of the developed mathematical production estimation model. To reinforce the yield determination at field-scale, the vigour of the selected plants in the field 16 (cv 'Nocchione') was measured during the growing season 2020 as vegetative trait to use for calculating the plant yield efficiency YE ($YE = yield * TCSA^{-1}$ where $TCSA$ represents the trunk-cross sectional area). The calculated YE of the ten selected plants in field 16 showed high uniformity, as reported in the Deliverable D5.5 “Fruit development and production monitoring” [15]. This parameter, which is more stable than the plant yield alone, was particularly useful for the development of the mathematical model for hazelnut yield estimation. Furthermore, to determine the quality of the nuts and the net yield excluding defective hazelnuts (especially empty nuts), the nut and kernel weight, width, thickness and height, nut and kernel shape, shell weight and kernel/nut ratio were recorded on sub-samples of 50 nuts per plant in the laboratory. The most important trait revealed during the nut and kernel traits characterization was the incidence of empty nuts at harvest time, which was slightly high, with mean values equal to 14%. This trait was considered during the determination of the net yield per plant, subtracting from the gross yield per plant the percentage of empty hazelnuts detected during the lab activities, similarly to what happens in the hazelnut trading sector.

Regarding the fruit development and production monitoring protocol presented in PANTHEON, the proposed approach has focused on the development of tools for the estimation of the production in large-scale orchards based on sparse measurements in space and time. This design choice was dictated by the observation that a constant monitoring of plants in a large-scale orchard is clearly unrealistic.

A starting assumption to develop this approach so is the observation that all trees in a same sufficiently small area of a plantation are subject to similar conditions and thus have comparable losses in production. This fact allows to estimate the state of unmeasured trees and to assess the total production based only on measurement of some plants.

Data from the harvest season of 2020 at the PANTHEON experimental orchard showed that indeed the rate of nuts losses is fairly common for near trees and can be estimated based on previous year measurements. Based on the results obtained from the PANTHEON data, the proposed protocol aims at exploiting the presented properties to obtain a good prediction and update of the production estimation.

The protocol can be defined as follows:

SETUP

1. **Subdivision into areas.** The plot is divided in areas that can be considered homogeneous in terms of conditions (soil nature, exposition, type of irrigation, planting scheme) and treatment received by the plants. The more homogeneous these areas are, the better for the estimation.
2. **Identification of the rate $\hat{\kappa}_j$ (nuts losses rate) for each subarea** based on several measurements of different plants during at least one growing season.

ESTIMATION PROTOCOL DURING THE GROWING SEASON

1. Use of the initial measurements of some plants in the different subareas to estimate a given efficiency to **compute the initial conditions of all plants**.

2. Monitoring of the **production evolution based on the identified model and possible punctual measurements**. The use of a model to predict the evolution of the production allows us to obtain a reasonable estimation of the final production, but this estimation can be improved using punctual measurements of some plants at different instants of the growing season. To do so we propose the use of an Extended Kalman filter with intermittent observations.

VALIDATION OF THE PRODUCTION MONITORING APPROACH

To validate the presented approach regarding the estimation of the total production of hazelnuts, we used the data collected in 2020 regarding 10 plants in two steps. First, we validated the proposed methodology by obtaining an estimation of the initial number of nuts at the beginning of the season. Then, we validated the estimation of the production given by the model of nut losses assuming the knowledge of these initial conditions.

Estimation of the initial conditions

To show how the computation of the average YE made on a small percentage of trees can be reliably extended to all the trees to compute the initial number of nuts, we carried out the following validation procedure using 20% of our data (i.e., two randomly selected plants) to compute YE and the rest to validate. This procedure was repeated on all N_c possible combinations of datasets.

The validation procedure is composed of the following steps:

1. We compute the average yield efficiency YE using the data from two plants;
2. We compute the initial conditions as $\hat{x}_i\,(t_0) = YE\,\frac{TCSA_i}{\varpi_i}$ for the other eight plants;
3. We compare the estimated initial conditions $\hat{x}_i(t_0)$ with the measurement $x_i(t_0)$
$$e_i = \left|\frac{x_i(t_0) - \hat{x}_i(t_0)}{x_i(t_0)}\right|$$
where i is the index of the selected plant;
4. We compute the average error of all plants

$$error = \frac{\sum e_i}{N-2}$$

where N is the total number of plants.

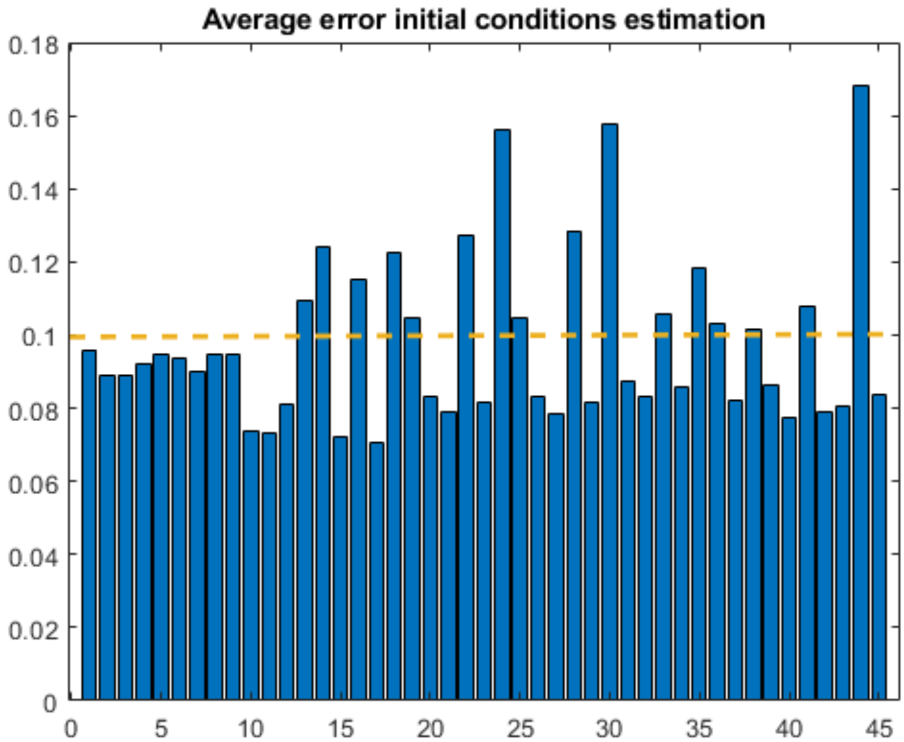

Figure 45. Average error in the estimation of the initial conditions

Figure 45 shows the average percentage error in the estimation of the initial conditions based on the efficiency relationship for all computed datasets. It can be observed that this error is mostly under 10%, providing an average for all the datasets equal to 9.76%. These are promising results given the fact that only two plants are used to estimate this correlation factor and the initial conditions.

Estimation of the losses rate

As in the previous step, we used 20% of our data to show that the losses rate $\tilde{\kappa}(t)$ estimated on these two trees can be extended to all the trees, obtaining a reasonable estimation of the production.

The procedure was also repeated on all N_c possible combinations of datasets, following the methodology represented in Figure 46.

The considered procedure is composed of the following steps:

1. We identify the loss rate $\tilde{\kappa}(t)$ using the data from two plants;
2. We compute the solution of the model $\hat{x}_i(t_3) = e^{-(\hat{\kappa}+\tilde{\kappa}(t_3))t_3} x_i(0)$ with $x(0)$ the first measurement of the other eight plants and t_3 is the time of the harvesting;
3. We compare $\hat{x}_i(t_3)$ from the estimated model with the real measurement $x_i(t_3)$
$$e_i = \left| \frac{x_i(t_3) - \hat{x}_i(t_3)}{x_i(t_3)} \right|$$
where i corresponds to the index of the selected plant;
4. We compute the average error of all plants:

$$error = \frac{\sum e_i}{N-2}$$

where N is the total number of plants.

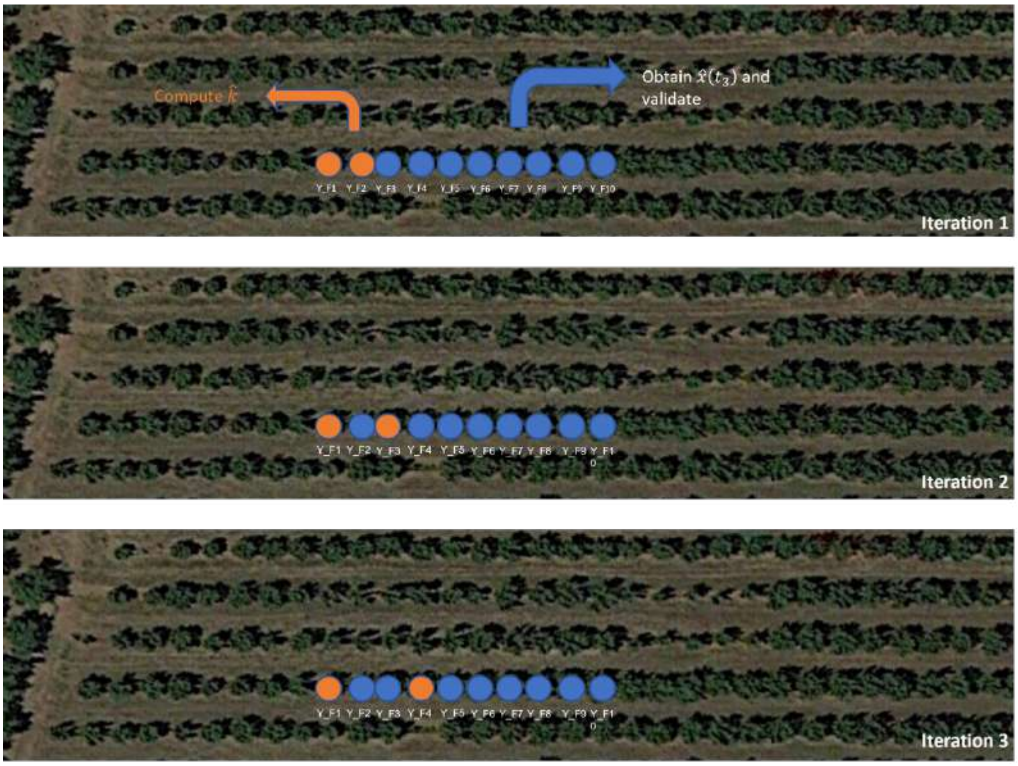

Figure 46. Procedure of selecting the training and validation datasets.

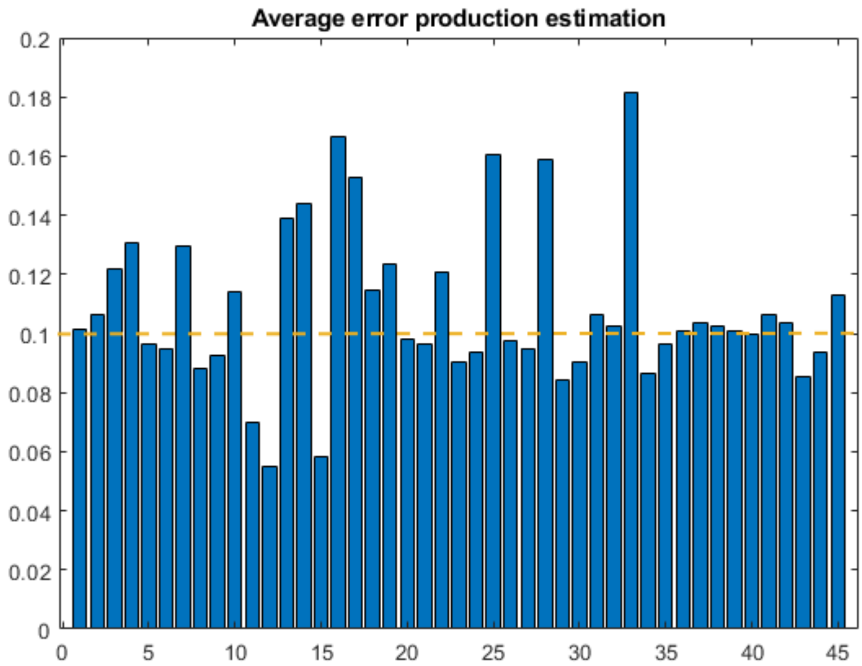

Figure 47. Average error of the percentage of the production for all N_c combinations

The results for all computed datasets are shown in Figure 47. The figure highlights that in most cases the estimation error is under 10% providing indication that the response of all plants is similar enough to use some measurements to estimate the others. Further details can be found in the Deliverable D5.5 “Fruit development and production monitoring” [15].

4 Bibliography

[1] C. Potena and N. B. Rosselló, "H2020 PANTHEON, Deliverable 6.1, Robotic Vehicles Field Validation".

[2] N. B. Rosselló, A. Gasparri, E. Garone and R. F. Carpio, "H2020 PANTHEON, Deliverable 3.1, Manual of the Ground Vehicle Prototypes".

[3] R. Carpio, C. Potena, J. Maiolini, E. Garone, G. Ulivi and A. Gasparri, "A Hierarchical and Compact SLAM Architecture for Autonomous Vehicles in Large-Scale Orchard Farming, manuscript in preparation.," *Journal of Field Robotics,* 2021.

[4] R. Carpio, C. Potena, J. Maiolini, G. Ulivi, N. B. Rossello, E. Garone and A. Gasparri, "A Navigation Architecture for Ackermann Vehicles in Precision Farming," *IEEE Robotics and Automation Letters,* pp. 1-1, 2020.

[5] E. Graziani, "H2020 PANTHEON, Deliverable 6.2, SCADA System Integration and Field Validation".

[6] E. Graziani, "H2020 PANTHEON, Deliverable 3.4, User Interface".

[7] S. Lamprecht and S. Ahlswede, "H2020 PANTHEON, Deliverable 4.2, 3D Tree Models".

[8] M. Drais, S. Turco, C. D'Attilia and A. Mazzaglia, "Development of a quantitative PCR assay for the detection of Monostichella coryli, the causal agent of hazelnut anthracnose".

[9] M. Drais, L. Rossini, S. Turco, A. Faluschi and A. Mazzaglia, "A novel adaptation of the life tables analysis technique to fungi: modelling germination and mycelium growth rates of Monostichella coryli at different constant temperatures".

[10] S. Turco, A. Grottoli, M. I. Drais, C. D. Spirito, L. Faino, M. Reverberi, V. Cristofori and A. Mazzaglia, "Draft genome sequence of a new Fusarium isolate related to Fusarium tricinctum species complex collected from hazelnut in Central Italy," *Frontiers in Plant Science,* 2021.

[11] V. Cristofori, L. Giustarini, M. Paolocci, E. Garone, S. Lampretch and A. Gasparri, "H2020 PANTHEON, Deliverable 5.2, Suckers' Management Control".

[12] M. Santilli, R. F. Carpio, J. Maiolini, M. Lippi, V. Cristofori and A. Gasparri, "An Autonomous Suckers Management Architecture for Large-scale Hazelnut Orchards (under review)," *IEEE Transaction on Automation Science and Engineering,* 2022.

[13] M. Santili, V. Cristofori, C. Potena, R. F. Carpio, C. Silvestri and M. Paolocci, "H2020 PANTHEON, Deliverable 5.3, Pruning Management Protocol".

[14] S. Ahlswede, S. Lamprecht and R. Retzlaff, "H2020 Pantheon, Deliverable 4.5, Pest and Disease Detection".

[15] V. Cristofori, C. Silvestri, M. Paolocci, E. Garone, R. Nico Bono and M. Lippi, "H2020 PANTHEON, Deliverable 5.5, Fruit development and production monitoring".

[16] M. Contarini, M. Lippi, I. M. Drais, S. Speranza and A. Mazzaglia, "H2020 PANTHEON, Deliverable 5.4, Pests and diseases monitoring and control".