Final Report

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The Applications of Remote Sensing in Plant Health (PHeRS)

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Contents

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2. Short project report

2.1 Executive Summary

In a world of increasing globalisation and climate change, the risks to crops and forestry from the introduction and onset of harmful pests (pathogens, vectors and insects) have increased significantly in the last years. Within this context, European agriculture and forestry are facing the challenge of a great pressure of harmful pests, including invasive alien species, which highly impact in yield and quality losses. A sustainable rural and forestry economy is therefore highly dependent on the healthy status of plants. Control means against most of harmful pests are difficult or may not even exist. Preventive measures based on the early pest surveillance and detection are therefore, economically and environmentally, more efficient than eliminating phytosanitary outbreaks from which the infestation can fast spread. Surveillance is therefore essential as a valuable source of information for the timing application of phytosanitary measures to prevent pest establishment and spread (ISPM 6, 2018). Once in, eradication and/or pest control should soon be applied, and their effectiveness assessed. NPPOs have limited resources for the implementation of effective surveillance and phytosanitary measures. Remote sensing, spatial mapping (geographical information system) and computer applications can make it much easier for NPPOs to acquire, manage and map data on a large scale and on a small scale in real time, providing effective support for decisions to be taken.

Remote sensing is the science of gathering data on an object/area without making physical contact. Aircraft, satellite and drone-based cameras and sensors are used to measure reflected and/or emitted electromagnetic radiation. This information, often captured as images, can then be analysed to extract additional, valuable data which can be mirrored in a GIS environment for spatial mapping.

In the last decade great progress has been achieved in the use of remote sensing for the detection and mapping of several pests and relative host species at territorial basis. However, much research on this subject is still ongoing, but few applications have been made in plant health programmes due to some gaps that need to be identified and addressed.

The project aimed to bring together experts from research organisations and companies to share knowledge on remote sensing applications in the plant health sector. The partners were interested in:

- State of the art, research needs and gaps on remote sensing methodologies in plant health, including the use of GIS and IT tools.
- Advancements of research for the qualitative and quantitative identification of host plant species by remote sensing over larger areas.
- Advancements of research on remote sensing applications for the identification of specific pests over larger areas.

At the beginning of the project a skype meeting was organised to learn about the partners' activities and to exchange experiences and points of view on the subject.

A workshop was subsequently held at the European Commission Joint Research Centre (JRC), Ispra, Italy. Representatives from the six partner organisations presented their work on remote sensing applications in plant health including, species classification, health analysis, tree counting and the scaling up and modelling of remote sensed spatial data.

Discussions focused on similarities of approaches, identification of gaps and suggestions to fill these gaps with the support of research. The PHeRS consortium mapped past and current research activities across Europe, reviewed the state of the art of remote sensing technologies applied to plant health and identified benefits and limitations in the framework of official activities such as pest surveillance and host mapping, pest detection and outbreak monitoring.

The outcomes of the project were also presented at the EPPO/Euphresco Scientific Colloquium ‘Perspectives on the Use of Remote Sensing in Plant Health’.

2.2 Project Aims

National Plant Protection Organisations worldwide are increasingly looking for new tools that allow early detection of infected plants and for the classification of host plant species to aid in monitoring and to minimise the impacts of pests (Brown *et al*., 2016; Gandolfo & Mortimer, 2013). Remote sensing is one such tool that can be used to identify vegetation stress caused by pests (Ciesla, 2000), offering a practical and economical means to study vegetation health (Langley *et al*., 2001) and detect host species to help target on the ground inspections (Brown *et al*., 2016; Pinter *et al*., 2003).

Precise and time saving methods are therefore essential for early pest surveillance and detection in large areas, for the management of outbreaks, for the evaluation of the effectiveness of the applied phytosanitary measures, thus optimising the limited resources available in NPPOs. Images from satellites, piloted planes and drones can provide great support for the rapid and timely identification of plant health risks, including the mapping of host plant species. For example, the reflected colour observed from space can be used as an indicator of plant stress associated to the presence of a pest. This knowledge could help in assessing the risk of outbreaks and patterns of spread across the country. It could also improve the country’s inventory of host plant species and their distribution. Remote sensing may also help to assess the health of plants without visiting a site in person. However, there are still few operational applications of RS because several gaps are limiting their use in plant health.

This short project aims to bring together public research organisations and private companies, working towards similar goals in the applications in plant health of remote sensing, for supporting research funders in the identification of priority areas of research in plant health. Specifically, the project accounts for five research groups in the EPPO region and one group from USA. PHeRS partners have been using remote sensing in plant health for many years and for various applications, including, species classification, health analysis, tree counting and the scaling up and modelling of remote sensed spatial data.

Objectives of this project are:

- sharing of knowledge and exploration of past and current research, focusing mainly on the research carried out in each organisation and company partner;
- reporting on the advantages and limitations of remote sensing applications, with attention also to integration with GIS and IT tools;
- reporting on the needs for future research in this field to support funders of phytosanitary research.

2.3 Main Activities

Project activity was organised into four Work Packages (WPs) and structured as follows:

WP 1: Project management and coordination.

WP 2: State of the art, research needs and gaps on remote sensing applications in plant health; integration of RS with GIS and IT tools.

WP 3: Advancements of research on remote sensing applications in Plant Health.

Task 3.1. Advancements of research for the qualitative and quantitative identification of plant host species by remote sensing over larger areas, including geographical and species variations and automatic tree counting.

Task 3.2. Advancements of research on remote sensing applications (e.g. thermal imagery) for the identification of specific pests over larger areas.

WP 4: Project results dissemination.

In the first phase, the project brought together key remote sensing experts from across Europe to map and review current work in this area and identify research requirements and gaps. The idea was to forge new working collaborations and build enthusiasm for these new technologies in plant health and quarantine programmes.

In the second phase, the experts have worked collaboratively to produce a report on the past and current state of research at each partner's organisation/institution/company, specifically identifying work being undertaken on remote sensing to (a) identify host trees remotely, (b) to pin point diseased trees. Moreover, the integration with GIS and IT tools was also considered for a more accurate mapping and on-site data acquisition of remotely sensed information. Gaps of research were identified and considered for developing future research lines.

<u>Kick off meeting.</u>

The kick off meeting was organized on the 6th of July 2017 through skype. Partners presented their institutions/company and briefly reported the past and present activity in plant health with the use of remote sensing technology. We learned about each other's activities and exchanged the partners' opinions on the subject in order to define a preparatory programme for the workshop.

<u>Workshop</u>

A workshop was held at the European Commission Joint Research Centre (JRC), Ispra, Italy on the 28th November 2017. It brought together partner scientists who are working on the introduction of remote sensing techniques into plant health. Attendees were from CIHEAM of Bari (Italy), Fera Science Ltd. (Fera) (United Kingdom), Defra (United Kingdom), CREA (Italy), Terrasystem (Italy) and JRC (based in Italy). Each organisation has been developing remote sensing techniques in plant health as outlined in this report. Participants shared detailed information on their expertise in remote sensing and research activities were presented:

- CIHEAM of Bari has developed an automatic citrus tree counting algorithm and a semiautomatic algorithm for the identification of citrus trees infected by *Citrus tristeza closterovirus* (CTV) using multispectral satellite images (Gualano *et al*., 2012 ; Santoro *et al*., 2013). In addition, they have also applied a methodology of manual photointerpretation of olive trees with symptoms of Olive Quick Decline (OQD) from aerial images to support the official monitoring of *Xylella fastidiosa* in Southern Italy (Gualano, 2017). They have also developed dedicated IT field applications for the inspection of symptomatic trees which were remotely identified, e.g. XylApp$_{\text{Puglia}}$ (Santoro *et al*., 2018) and for supporting contingency plans for Xylella in NENA countries,e.g. XylApp$_{\text{NENA}}$ (FAO-RAB project).The use of a dedicated application for *Xylella fastidiosa* is now under preparation for its use at European level (e.g. XylApp$_{\text{EU}}$ in the framework of the H2020 EU project ‘Xf-actors’) and to other regulated and not regulated pests (e.g. PhytoApp$_{\text{pests}}$). Current available sensors are not pest specific. Therefore, research is now focusing on early pathogen detection through the selection of ‘a package of wavelenghts’ and new vegetation indices for developing pest-specific sensors. These results could be achieved through the study of metabolomic profile associated to the infection (e.g. *Erwinia amylovora*, *X. fastidiosa)* and will lead to the use of hyperspectral images for early pathogen detection (Rizzuti *et al*., 2018).

- Fera has developed automatic classification algorithms for identifying individual tree species to determine possible host species distribution for pests and diseases (Brown *et al*., 2016; Brown and Butler 2016). Fera is collaborating in the development of lightweight snapshot hyperspectral cameras that are unmanned aerial system (UAS) mountable. FERA is currently working on a project to use temporal UAS acquired imagery to train freely available satellite data (Brown *et al*., 2017). https://www.fera.co.uk/environmental-science/remote-sensing-and-mapping

- APHIS USDA has conducted research to evaluate hyperspectral image (HSI) datasets to map green ash and ground truth data. Overall the ground truth and field spectra do not always provide a unique differentiation of green ash from all tree species. Research is now being focused on the utilisation of UAS in pest management programs, such as boll weevil (*Anthonomus grandis grandis*) eradication efforts, for finding host plants.

- Terrasystem and CREATerrasystem, in collaboration with the University of Tuscia, have developed airborne sensors, algorithms and models for the detection of stress induced by pathogens in different tree crops (vine, olive, hazelnut). They are examining upscaling from airborne data scale (<1m spatial resolution) to high-resolution satellite data scale (up to 5-10m spatial resolution) in Southern Italy, in order to cover larger areas. http://www.terrasystem.it/en/index.htm, https://www.crea.gov.it/it.

- The European Commission Joint Research Center has developed big data analysis techniques for the counting of crop trees over large areas and assessing losses to disease, and for the evaluation of tree health from multiple Earth Observation data sources. They are evaluating leaf-level indicators measured with fluorescence and reflectance sensors for the scaling up to images acquired by airborne hyperspectral cameras. Additionally, they are adapting statistically-based models that were built with narrow-band hyperspectral indices and thermal data that have been demonstrated as useful for mapping the symptoms of verticillium wilt in olive and almond red blotch, for the *Xylella fastidiosa* outbreak in southern Italy and elsewhere https://ec.europa.eu/jrc/en.

The presentations were given in two sets of three with a discussion after each set of three presentations. From these discussions the group were able to tease out areas of overlap and potential gaps in the current research. It was clear that the project partners have been working on a number of remote sensing methodologies with some overlap. Tree counting and species identification for host mapping is a clear area of research amongst the project partners, utilising, multispectral, hyperspectral and thermal data in their workflows. Understanding the location and abundance of tree species enables targeted inspection in an outbreak situation. Species information also allows for pest/disease spread to be modelled prior to an outbreak occurring, allowing pathways to be mapped and mitigation/management strategies to be planned and put in place. Another common theme is the development of automatic algorithms for data analysis and scaling up from detailed laboratory analysis on a foliar scale to UAS, airborne and satellite scale.

Potential research gaps identified during these discussions included sensor limitations, e.g. lack of shortwave infrared (SWIR) data capture in very high-resolution sensors, which would enable detailed water stress analysis, data sharing, normalisation of methods for data acquisition and processing, spectral measurement campaign, collaboration and resources. All these gaps pave the way for further collaborative research, which will be discussed later in this report.

The second half of the workshop was open to a discussion around three topics: identification of research requirements, future advancements of research and preparation of the project report. The discussion naturally moved to how we would structure a final report, what storyline would we follow for a detailed technical report. It was decided to follow a pest outbreak scenario and what remote sensing work is being conducted at different stages of the timeline.

A full technical report on the activities of the PHeRS project is being prepared for publication in the EPPO Bulletin. The report has been structured as follows:

1. Introduction: main fruit tree crops and forestry in EU; major quarantine pests affecting fruit tree crops and forestry under EC plant health directives which have been also considered for remote sensing applications as target pests; pest surveillance and detection; and remote sensing applications (with the combination with GIS and IT tools) in plant health by project partners.

2. Pest outbreak scenario: - *Preparedness to pest entrance* (surveillance programme; host mapping; mapping of pest risky entry points); - *Pest outbreak management* (pest monitoring, eradication of infected plants; spatial mapping, modelling and statistical analysis; containment measures); *Benefits assessment* (Effectiveness of applied phytosanitary measures).
3. Research and operational gaps: remote sensing technologies; platforms and sensors; remote sensed information; data processing; statistical analyses; GIS and IT tools.
4. Research needs: user's friendly, low cost and best performing methods and tools (e.g. sensors, platforms).
5. Conclusions and recommendations

This summary report is a condensed version of a full technical report.

2.4 Major findings

With traditional methods inadequate for prevention, control and eradication, remote sensing integrated with geographic information systems (GIS) and IT tools offer potential to combat pests through development of risk maps and pest prediction maps which show areas susceptible to pest infection (Kazmi and Usery, 2001).

2.4.1 Target quarantine pests affecting fruit trees and forestry

Some regulated pests under EC plant health Directives were selected as target pests, being already studied for applications of remote sensing technologies. In few cases, remote sensing was also used in official NPPOs programmes. However, pests and relative host species, mentioned throughout this report, may not currently be directly relevant to the specific country of the reader; the remote sensing techniques used in the study of these pests can be translated to interpret differing causes of plant stress.

- *Xylella fastidiosa* - plant bacteria inducing numerous diseases in plant species (included in the A2 EPPO list).
- *Citrus tristeza closterovirus* - the causal agent of tristeza disease mainly in Citrus species (A2 EPPO list).
- '*Candidatus* Phytoplasma vitis' - the causal agent of Golden flavescence disease in grapevine (A2 EPPO list).
- *Agrilus planipennis* - Emerald ash borer (A2 EPPO list).
- '*Candidatus* Phytoplasma phoenicium' - the agent of Almond witches' broom (A1 EPPO list).
- *Bursaphelenchus xylophilus* - Pinewood nematode (A2 EPPO list).
- *Fusarium circinatum* - the agent of pitch canker on pine trees (A2 EPPO list).
- *Phytophtora ramorum* - the agent of sudden oak death (A2 EPPO list).

2.4.2 Technology and Techniques

Any country must protect cultivated, forestry and wild plant species by preventing the introduction and spread of dangerous pests through timely and effective applications of phytosanitary measures. One of the main mitigating measures is pest surveillance/monitoring in order to provide early detection of the presence of a pest. Remote sensing can help to identify pests even when symptoms/damages are not visible to naked eye.

Platforms and sensors

There are many platforms and sensors designed for the acquisition of remotely sensed data, ranging from satellite, airborne and most recently UAS technology. These platforms can mount various remote sensing sensors that can contribute in different ways to the classification of plant host species and to the monitoring of health status of plants, thus the presence of biotic stress. In general, four main groups can be recognised: optical, microwave, thermal and hyperspectral sensors. These sensors have various spatial, spectral and temporal resolutions and offer information valuable for certain crop types and certain plant health status. It is important to highlight that most of these sensors, with the possible exception of hyperspectral, can provide information on pest disease/damage, not on presence/absence of a given pest. In the choice of sensors and data, even if a case-by-case approach should be always used, some general indications can be given on a crop-group basis.

Take for example forests and/or forest crops. These are permanent and composed of individuals of usually relevant dimensions with continuous cover. They are easier to monitor with satellite data, or airborne data. The use of UAS is less recommended if operating in large areas with dense cover; however, for smaller woodland analysis UAS are a viable option. Conversely, fruit trees (different planting systems, no continuous pattern etc.) require higher resolution sensors with a great analysis capacity. Optical information is used to identify photosynthesis levels and productivity trends thanks to vegetation indices, and this represents a first tool to detect areas affected by infections, which usually show a decrease in the value of these indices. With the Sentinel-2 (part of the EU Copernicus programme) data now available, and its increased spectral (but also spatial) resolution with respect to Landsat data, more indices are available with freely available data, which broaden the opportunity of health status detection.

Important information of forest structure/volume and water content, and their modifications (gaps in cover, mortality, dry conditions or loss of branches and foliage) can be derived by Synthetic Aperture Radar (SAR) data. Sentinel-1 represents a true innovation with freely available data that is not exploited enough and should be included in the operational monitoring of forest crops.

Thermal information is always relevant in the detection of stress conditions. In satellite data, the spatial resolution is usually far too low for proper monitoring and thermal data, collected with airplanes and used for health monitoring, are not common. However, thermal cameras for UAS are now becoming readily available.

Hyperspectral data, presently available from airborne surveys and more recently UAS only, is high quality information, able to provide highly detailed spectral data resulting in the discrimination of differing sources of stress, thus helping in the identification of certain pathogens that produce characteristic plant damage. However, the processing of these data is very demanding, acquisition is expensive and its use for disease monitoring is still quite scarce.

Statistical analyses

Another important limitation of hyperspectral optical sensors is the vast amount and complexity of data gathered. In order to effectively utilize the data from the optical sensors (imaging and non-imaging-based) for the identification and diagnosis of the disease, advanced methods of statistical analyses are essential. In general, tasks such as the following are required from RS data:

- early identification of a disease;
- differentiation between similar diseases;
- separation between biotic and abiotic stresses;
- quantification of the severity of the disease.

These goals must be achieved with a higher accuracy or be equivalent to the requirements achieved from traditional methods and with shorter response times. Hyperspectral RS data analysis methods are continually introduced in the science of plant diseases and may be classified in four large-scale groups which include:

a. univariate techniques of correlation, regression and analysis of variance (ANOVA) of the presence of disease and/or its seriousness with the spectral response, in specific or subinterval narrow bands of the wave-lengths of the spectrum (Huang *et al*., 2012);

b. univariate techniques of evaluation and identification of specific spectral indices of the vegetation by narrowband (SVIS) sensitive to the presence of the disease (Reynolds *et al*., 2012; Mahlein *et al*., 2013; Stilwell *et al*., 2013).

c. multivariate techniques of Data Mining applied to processing of spectral data for the reduction of dimensionality and extraction/selection of features (Grisham *et al*., 2010; Bauriegel *et al*., 2011);

d. techniques of Machine Learning and of Classification, parametric and non-parametric, supervised and unsupervised for cluster identification (classes of homogeneous groups) based on the presence/absence of the disease and/or of relative levels of seriousness (Moshou *et al*., 2012; Mahlein *et al*., 2012; Al Naasan *et al*., 2018).

In this context, researchers have recently identified sensors and methods of Data Mining for the survey/collection of data, identification and the quantification of diseases in plants (Sankaran *et al*., 2010).

If the sensors are able to capture subtle optical properties of plants in different regions of the electromagnetic spectrum (also beyond the range of the visible), thereby allowing for the detection of early changes in plant physiology induced by forms of biotic and/or abiotic stress, the possibility of better analysing the enormous wealth of information contained in the remotely sensed data is relied upon for the appropriate choice of the techniques of the processing statistics used. In addition to the statistical classification models, many non-imaging spectroscopy-based studies utilise vegetative indices to evaluate the variance of spectral reflectance in various dichotomous conditions (healthy or diseased plants).

2.4.3 Remote sensing in the pest outbreak scenario

Preparedness - Lessons learnt from previous disease outbreaks indicate that the collection of historical and ancillary information per crops or agriculture unit is fundamental to prevent and/or manage early stage health issues. This implies the setup, often with the support of local agriculture organisations, of systems able to store digital and non-digital information mainly on: crops (e.g. location and extent of species), agricultural practices, phenological phases, environmental and climate data, soil information, historical presence of pests, risky entry points (e.g. nurseries, airports) etc.

This phase is of utmost importance in order to organize the surveillance and monitoring activity on a large scale with accuracy, quantifying human and financial resources (target area, number of host plants etc.) for field monitoring in a target way.

Remote sensing could support the large-scale mapping of potential hosts (based on the spatial location of crops type, tree species etc.) which can be visualized in a GIS environment for data analysis at risky points (e.g. quantification of host species nearby nurseries, airports). A number of host mapping studies have been conducted by the project partners, including the use of fusing optical and Synthetic Aperture Radar (SAR) data to perform classifications of higher accuracy. Hyperspectral data has been highlighted as a technology that could both improve classification accuracy and have capacity for discriminating between the damage caused by different pathogens. Pest prediction maps from hyperspectral images can become a powerful tool for early pest detection, thus indicating priority provide.

Management - Once a pest outbreak is identified a rapid demarcation is necessary to set up phytosanitary measures in the infected zone and in the buffer zone. The buffer zone should be soon monitored for evaluating the extent of the infection and define precisely the delimitation of the buffer zone. Eradication measures should soon applied for pest elimination or containment. Pest spatial and temporal spread, and damage assessment are extremely important to be evaluated after eradication for adopting efficient phytosanitary measures.

Remote sensing methods have been used to detect the effects caused by diseases, such as changes in the leaf optical properties due to pigment degradation and changes in their concentration, reduction in green canopy biomass, and increases of canopy temperature (Mahlein *et al.*, 2012). Spectral indices located at specific wavelengths, where photosynthetic pigments changes occur due to stress conditions, have been used to detect differing levels of stress.The use of thermal data to detect stress caused by stomatal closure has also been implemented.

The project partners support the option of collecting geographical explicit information on pest presence in a centralised effort: this database, if opened to scientific institutions, can support research into applied remote sensing to plant health monitoring, increasing the evidences and methods to use this important tool in favour of improved agriculture management.

Cost-benefit assessment - The total cost and the cost-benefit ratio for each strategy should be estimated over the short and long term. The option to take no action, or to take a pest management approach, should be considered as well as eradication options. All feasible options should be described or discussed with decision-makers. Anticipated advantages and disadvantages, including cost-benefit should be outlined to the extent possible.

Remote sensing can provide information on the effectiveness of the applied phytosanitary measures the spatial and temporal pest spread, thus estimating damage occurring at territorial basis.

2.5 Conclusions and recommendations to policy makers

Remote sensing is therefore essential for pest surveillance and detection in large areas, for the management of outbreaks, for the evaluation of the effectiveness of the applied phytosanitary measures, thus optimising the limited resources available in NPPOs. Globally remotely sensed data are being used considerably in the classification of species and the study of plant health. However due to certain constraints, including the cost of data, a lot of the work is focused around the use of freely available satellite data. These data do not have the spatial resolutions required for highly accurate monitoring of plant health. However, research institutes/organisations and private companies, including those involved in this project, are working on developing methods to use more expensive data to train algorithms and software that use free data (the use of very high-resolution datasets to identify spectral signatures that can then be identified in the satellite data) in order to upscale analysis from a laboratory/local scale to regional/national scale. Therefore, beside a lot research has being conducted on pests affecting several crops (e.g. grapevine, kiwifruit, citrus, olive), currently remote sensing methods are not integrated into institutional practices, supporting NPPOs in the management of harmful pests.

This report has identified areas where remote sensing applications can provide monitoring at different stages of the pest and disease management cycle. Each partner involved is working extensively with applications in remote sensing of plant health, however these applications are generally at the research stage. There is a research and operational gap, and this is the gap that needs filling. A serious limitation in the application of remote sensing is still the cost of the imagery and skills for data processing. When the need for repeated acquisition of imagery, to follow infection spread or capture crop/tree phenology for classification, is considered, a large proportion of remote sensing research/application is usually designed and performed with freely available optical imagery, for example Landsat and more recently the Sentinel series of satellites. Often the spatial resolution of these platforms is not sufficient to resolve the individual objects of interest, trees, plants, crops, for example. Therefore, a lot of research between the project partners has been how to use small areas of very high-resolution data (spatial and spectral) to train algorithms and software that use the freely available imagery over larger areas of land, thus keeping the cost as low as possible.

Many of these applications are getting closer to market, in terms of being close to becoming an operational tool for plant health monitoring and inspection. The use of UAS and airborne acquired imagery to train algorithms and software that use freely available satellite data to classify tree species over large areas, as mentioned above, is being developed and in the later stages of providing a prototype.

Remote sensing is a technique that will continue to rapidly grow and improve monitoring for plant health. Over the past four years, during which some of the project partners have been using UAS to acquire data, this technology has progressed dramatically, with easy to use, programmable UAS system paired with relatively cheap, light weight, scientific grade sensors. It could, in the future be viable for a plant health inspector to be equipped with a drone, upload the data to the cloud and select the processing required and receive a result in the field. To get here, more research and development needs to be conducted, specifically in the area of managing and processing large sets of data.

Additional tools such as field applications for identifying remote sensing data outputs can support accurate ground data acquisition (e.g. XylApp) while spatial mapping (geographical information system), modelling and statistical analysis software can be used to manage surveillance data and to facilitate their presentation and reporting.

This is a very fast-moving area of plant health research. The partners involved in this project have all benefited from understanding what research is being undertaken in other organisations. There is a certain amount of overlap between the project partners activities but also synergies and many areas of future collaboration; these include but are not limited to programmes/projects towards normalisation methods of data acquisition and processing, the building of sharable spectral libraries and collaboration that could partially overcome the issue of lack of resource.

We can conclude as follows:

There are many platforms and sensors designed for the acquisition of remotely sensed data, ranging from satellite, airborne and UAS technology. These platforms can mount various remote sensing sensors that can contribute in different ways to the monitoring of plant biotic and abiotic stresses. Three main groups of sensors can be recognised:

- optical (RGB, multispectral/hyperspectral)
- thermal
- microwave

These sensors have various spatial, spectral and temporal resolutions and offer information valuable for certain plant/crop types and certain plant health status. Most of these sensors, with the possible exception of hyperspectral, can provide information on pest disease/damage, not on presence/absence of a given pest.

Major limitations in the application of remote sensing in plant health are:

- the low resolution of freely available satellite platforms (e.g. EU Copernicus programme)
- the high costs of airborne high resolution imagery
- few, expensive and high weight sensors available in the market
- no pest-specific sensors available

- lack of harmonized data quality
- and the lack of skills for data processing and interpretation with a competence in plant health.

In the choice of platforms, sensors and data, some general indications can be given on a plant/crop-group basis.

In consideration of the above-mentioned limitations, remote sensing methodologies which are currently applicable in pest monitoring programmes are the followings:

- Sentinel series of satellites (part of the EU Copernicus programme) are freely available for large area classification (vegetation classification mainly of pest-host plants of homogeneous cover) and higher temporal resolution.
- Other platforms provide higher resolution images (spatial and spectral) but are expensive.
- Application of semi-automatic and automatic plant counting (e.g. plant mapping; precise sampling procedures).
- Application of pest recognition procedures (e.g. predictions maps for *Citrus tristeza closterovirus*, *Xylella fastidiosa*).

Based on the mentioned limitations, future research should focus on:

- <u>Identify areas of the electromagnetic spectrum, ‘packages of wavelengths’</u> for detecting specific biotic and abiotic stresses. This result could be achieved through the study of plant secondary metabolites correlated to the infection and the correlation of the identified metabolites with specific wavelengths.
- <u>Development of most performing spectral Vegetation Indices (sVIs) for pest detection.</u> Different studies in the last few years have focused on the ability of spectral Vegetation Indices (sVIs) to detect specific diseases. To this aim a ‘package of wavelengths’ (pest-specific) could also be used for the identification of new and most performing sVIs.
- <u>Sensor technology</u> have various readiness levels, therefore progressing research sensor technology should continue through the TRL Levels.
- <u>Development/customising specific sensors</u> for plant health. New pest-specific sensors should also be user’s friendly (*low weight, small size etc.*) and cheap. This will allow a decrease data volume, a decrease processing time and a decrease analysis time.
- <u>Platform Technology progresses</u>. Development of drone platforms is progressing at pace, however current legislation restricts the use of drones and future drones for inspection purposes need to be:
    - Light
    - Cheap
    - More automation, pre-programmable to area of interest
    - Automatic collision avoidance and geofencing improvements to satisfy legislation.

- Near Ground Sensors Deployable on:
    - Drones

- Current machinery – tractors, mowers etc.
- Hand held
- Satellite platforms: ground results used for upscaling to satellite data to cover larger areas of land
- Highly accurate near ground instruments will enable more reliable ground results.

2.6 Benefits from trans-national cooperation

For this project the Euphresco programme has been instrumental in introducing a number of remote sensing experts from across Europe, some of whom were previously unknow to each other. The workshop highlighted the similarities in the consortia work, with the use of different techniques being extremely interesting.

Continued collaboration should start by discussing a research theme acknowledged in this report, whether that be concerned with shrinking the research and operational gap more efficiently by working collaboratively or by choosing an area that was highlighted as a research gap, for example, normalisation of acquistions/processing methodologies so that data and analysis could be shared more easily with colleagues across Europe.

The partners were in contact for the duration of this project and hope to continue this relationship in the future, starting with the writing of a joint paper for future peer reviewed publication. Members of CIHEAM of Bari, Italy are hopefully visiting Fera in York, UK in March 2019 to finalise the paper and to plan possible future collaboration. Anna Maria D'Onghia (CIHEAM of Bari), Paul Brown (Fera) and Pieter Beck (JRC) were also invited speakers and attending the EPPO Colloquium on Perspectives on the Use of Remote Sensing Technologies in Plant Health at the end of September 2018 in Paris. In this event they highlighted the need of enlarging the partnership to other EU and USA organisations/companies and the need of establishing an EU network of experts on Remote sensing in plant health.

This project has opened the door to a new research group, hopefully one that can work together in pushing remote sensing technology and techniques into plant health quicker and more efficiently.

3. References

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4. Publications

4.1. Article(s) for publication in the EPPO Bulletin

Manuscript in preparation.

4.2. Article for publication in the EPPO Reporting Service

None.

4.3. Article(s) for publication in other journals

None.

5. Open Euphresco data

Videorecording of the EPPO/Euphresco Scientific Colloquium ‘Perspectives on the Use of Remote Sensing in Plant Health’ is available on youtube and presentations made during the Scientific Colloquium ‘Perspectives on the use of remote sensing in plant health’ can be downloaded from Zenodo.