Downstream services for rice crop monitoring in Europe: from regional to local scale

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***Abstract*—The ERMES agro-monitoring system for rice cultivations integrates EO data at different resolutions, crop models and user-provided in-situ data in a unified system which drives two operational downstream services for rice monitoring. The first is aimed at providing information concerning the behaviour of the current season at regional/rice district scale, while the second is dedicated to provide farmers with field-scale data useful to support more efficient and environmentally-friendly crop practices. In this contribution, we describe the main characteristics of the system, in terms of overall architecture, technological solutions adopted, characteristics of the developed products and functionalities provided to end-users. Peculiarities of the system reside in its ability to cope with the needs of different stakeholders within a common platform, and in a tight integration between EO data processing and information retrieval, crop modelling, in situ data collection and information dissemination. The ERMES system has been operationally tested in three European rice-producing countries (Italy, Spain and Greece) during growing seasons 2015 and 2016, providing a great amount of NRT information concerning rice crops. Highlights of significant results are provided, with particular focus on real-world applications of ERMES products and services. Although developed with focus on European rice cultivations, solutions implemented in the ERMES system can be, and are already being, adapted to other crops and/or areas of the world, thus making it a valuable testing-bed for the development of advanced, integrated agricultural monitoring systems.**

***Index Terms*—Agriculture, Monitoring, Remote sensing, Modeling, Food industry**

I. INTRODUCTION

THE agricultural sector is facing important challenges due to several factors such as increasing worldwide food demand, increasing price competition due to effects of market globalization and food price volatility [1], and the needs for more environmentally and economically sustainable farming systems in developed countries [2].

In this context, availability of high-quality information concerning spatial and temporal variability of crops' distribution and status is of paramount importance to perform regional/continental scale monitoring, and to support innovative solutions at local/farm scale focused on improving productivity and reducing costs, while minimizing environmental impacts. This kind of information can nowadays be derived from the integration of high-quality geospatial data (e.g., remotely sensed images, meteorological) - fundamental to monitor both the main seasonal drivers of crop growth and overall crop status -, detailed, in-situ user-collected data, and crop modelling solutions able to simulate and forecast the effects of environmental conditions on crop development and final yield. Integrated agro-monitoring systems based on these three components constitute a key asset for monitoring and improving agricultural practices, thereby addressing the UN international millennium goal to reduce global poverty and climate change and the European Common Agricultural Policy striving for a more economically and ecologically sustainable agriculture.

A. Integrated agro-monitoring systems: from global to farm scale

The fundamental components of integrated agro-monitoring systems, either at regional or farm scale, are: *i)* reliable, operational and affordable sources of geo-spatial data (e.g., Remote

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Sensing data, weather data), *ii)* customized algorithm and solutions to generate value-added information from those data, and *iii)* ad-hoc Information Communication Technology (ICT) systems devoted to in-situ data collection, data-handling and dissemination of information to stakeholders.

Remote Sensing (RS) data from satellite or aerial platforms has been extensively used for crop identification and area estimation, crop yield estimation and prediction, and crop status and crop damage assessment [3]. Thanks to their capability to acquire synoptic and multitemporal observations, Earth Observation (EO) data provide a unique possibility for characterizing cropping systems over large areas, and are therefore a fundamental source of information to identify where and when crops are grown (e.g., [4], [5]), monitor seasonal dynamics (e.g., [6], [7]), and detect anomalous conditions (e.g., [8]). The importance of remote sensing in generating this kind of information has been also highlighted by the Group on Earth Observations Global Agricultural Monitoring Initiative [9]. In addition to these large-area applications, High Resolution (HR) and Very High Resolution (VHR) RS data from satellite, aerial or Unmanned Aerial Veichles (UAV) platform are a key component in local scale monitoring systems. This is due to their capability to highlight variations in crop status at field or sub-field level, thus allowing the application of Variable Rate Technology (VRT) management techniques (e.g., [10], [11]). Time series of satellite vegetation indexes images, as well as multitemporal biophysical parameters' (e.g., Leaf Area Index - LAI) maps or crop phenological maps derived from them, can also be used as inputs for spatialized application of process-based crop models exploiting regression, forcing or recalibration techniques. While this approach is common on a regional to continental scale (e.g., [12], [13], [14],[15]), only few studies tried to integrate remote sensing data and field measurements within process models for the simulation of crop growth and yield at field scale (e.g, [16], [17], [18]).

While RS data are an important source of information for characterizing the present or past state of crops, accurate weather data and forecasts provide crucial information for identifying and predicting adverse conditions (e.g., droughts, typhoons, etc.).

Weather data are also a basic input for many numerical models used for agriculture applications, such as hydrological models or crop growth models. Models exploiting these data, as well as ancillary information about crops' physiological characteristic, environmental conditions (e.g., soil characteristics) and management practices (e.g., irrigation, fertilization), have been used since the 70s to analyse the interactions between plants and the factors driving their growth. Starting from the mid-80s, modellers focused on developing management-oriented models suitable to support decision-making, (e.g., EPIC [19], CropSyst [20]). In the last years, technological developments also allowed application of these models at large-scale, often exploiting information derived from EO data as additional inputs (e.g., [21], [22], [23], [24])). In this context, models are often used for monitoring crop conditions and forecasting yields, at regional, national and continental scales (e.g., [25], [26]).

Finally, recent advances in mobile technologies facilitate the collection of user-generated contents. Mobile applications are therefore more and more proposed and used to collect and store detailed field information in a structured and efficient way [27]. This information complements RS and weather data, allows local stakeholders to systematically keep track of their farming activities, and may provide expert systems based on crop modelling with highly detailed information for parametrizing the required simulations.

While providing valuable assets for better analysing crop systems, the huge amount of information that can be derived from RS-, weather- and user-collected data, poses a technological challenge for developing operational agro-monitoring systems. In fact, these systems require robust ICT (hardware/software) solutions for automatized and interoperable management and publishing of heterogeneous high-dimensional data and information. In this context, the use of Spatial Data Infrastructures (SDIs) exploiting standard protocols and interfaces in a service oriented architecture paradigm is an acknowledged solution, and is mandatory in the European countries under the INSPIRE Directive[28]. SDIs support in fact the most common and basic requirements of geospatial data users: discovery, access, download and visualization of the data. Next to the technological aspect, usability of client-applications plays a crucial role for successful dissemination easily interpretable and timely information to various end-users, not necessarily skilled in using classical Geographic Information Systems (GIS).

Several examples of crop monitoring systems based on the aforementioned components were developed in the past years by researchers, institutional bodies or the private sector (mainly for precision agriculture applications). These systems can be divided in two main categories, which address the needs of different stakeholders: *i)* large-area early warning and yield forecasting systems, and *ii)* farm-scale systems for crop management support.

The former category is intended to provide decision makers information on potential crop production shortages, useful to coordinate relief initiatives and control food prices' volatility. For example, the Famine Early Warning Systems Network (FEWS NET - www.fews.net) [29] of the US Agency for International Development (USAID), created in 1985, is one of the most important providers of early warning and analysis on acute food insecurity. The Global Information and Early Warning System (GIEWS - www.fao.org/giews/) [30] is an FAO initiative with the specific objective of monitoring food supply and demand and other indicators for assessing the overall food security situation in the world. GEOGLAM's Crop Monitor (www.cropmonitor.org/) [31] was developed to provide periodic assessments of global crop condition in support of the AMIS (Agricultural Market Information System) market monitoring activities. Finally, a success story of continental scale monitoring with country level analysis is represented by the MARS (Monitoring Agricultural ResourceS, ec.europa.eu/jrc/en/mars) [32] European initiative of the Joint Research Center. All these systems exploit remote sensing data and crop modelling to provide their analysts with the information required for the edition of agro-monitoring bulletins. Since these systems are generally based on the use of coarse resolution satellite data (e.g., AVHRR (Advanced Very High Resolution Radiometer), MODIS (Moderate resolution Imaging Spectrometer), SPOT-VEGETATION, PROBA-V), their usefulness for national/regional scale applications can however be limited due to the insufficient spatial resolution. This kind of monitoring system is therefore more focused on developing countries, where even basic information about cropping systems is often lacking.

Farm-scale monitoring systems are instead more diffused in first-world countries, where they are used to support improvements of agricultural practices, aiming at increasing production, reducing costs and allowing a more rational and environmentally friendly use of fertilizers and agrochemicals. In this context, different Decision Support Systems (DSS) based on RS data, expert knowledge, agro-meteorological modelling and the use of mobile technologies for data collection, dissemination and exploitation have been developed. While experiences in this field are too many and too varied to review in this context, it is worth underlining the strong interest shown by the private sector in developing and commercializing these kind of applications. For example, FARMSTAR (www.farmstar-conseil.fr/) is one of the more advanced and successful experiences, and nowadays serves about 18.000 wheat farmers in France with value-added management information derived from remote sensing, crop modelling and expert knowledge. The Climate Corporation (www.climate.com/), which aims *"to build a digitized world where every farmer is able to optimize and flawlessly execute every decision on the farm"* was recently acquired by Monsanto. Other big companies such as John Deere, Bayer, BASF, DuPont are also currently building their own DSSs, either internally or through acquisition of start-up or innovative companies. Indeed, the market for precision farming services was estimated at 2.76 Billion USD in 2015, and was expected to grow by 11.7% in the 2015-2020 period [33]. In conjunction with commercial farm-scale monitoring systems, mobile apps are being increasingly used for farm management and data dissemination purposes. Next to supporting general farm management (e.g., stock ordering), these apps allow collection and recording of cultivation data (e.g., crop type, agro-chemical treatments), and sometimes integration with machinery to automate and increase efficiency of agro-practices (e.g., fertilization) by exploiting Global Positioning System (GPS) tracking and VRT techniques. A (non–exhaustive) list of some of the most used apps can be found for example at www.farmingwithapps.com/.

B. The ERMES agro-monitoring system for rice

From the above discussion, it is clear that development of agro-monitoring systems based on innovative technologies is a topic of strong interest, both for the scientific community and the private sector. It's however worth noticing that the two main branches of this sector, namely continental/regional scale monitoring systems and farm-scale systems for precision agriculture, are mostly developed separately. Nevertheless, they share strong commonalities: both strongly rely on RS data for getting a synoptic view of crop status and dynamics, and on weather data and forecasts to identify possible problems for crop growth. Additionally, both may benefit from the use of crop modelling techniques to better characterize and forecast growth processes (although this is rarely done at local scale, and from local observations to improve their accuracy. In this context, it is important to point out that, to our knowledge, no effort has been dedicated thus far to directly interface mobile data-collection apps with crop modelling engines.

Implementing more flexible, integrated monitoring systems, capable of addressing the needs of both local and regional stakeholders, could therefore create useful synergies, and allow a better overall picture of problems of the agricultural systems (which may range from highly-localized to continental). Furthermore, such systems could benefit from more efficient and effective hardware/software solutions based on modularity and re-use of approaches and assets.

The ERMES agro-monitoring system for rice aims to achieve such synergies. It was developed in the context of the ERMES FP7 project (An Earth obseRvation Model based RicE information Service – www.ermes-fp7space.eu), and integrates optical and radar remote sensing data from several sources and with different resolutions, regional and local weather data, state-of-the-art crop models and in-situ data collected by end–users in a single system, targeting both continental/regional and local-scale agro-monitoring. A focus of ERMES is in exploiting the possibilities offered by the European COPERNICUS programme (www.copernicus.eu/) for development of operational services based on free-of-charge RS data (e.g., Proba-V, Sentinel-1/2A). Additionally, ERMES aims at tightly integrating its crop modelling solutions within a structured data flow. This is achieved by *i)* developing automatic processes to transform RS data and products in inputs useful for the models, and *ii)* feeding in-situ data collected with a dedicated mobile application directly to ERMES customized modelling solutions, which in turn return useful field-scale information for farm management. Such an integrated, holistic crop monitoring system is rarely found in the literature.

In particular, ERMES focused its attention on European rice cultivations, due to both their economic and environmental importance, and the fact that no advanced monitoring systems for rice are currently available. For regional monitoring purposes, currently available systems such as MARS are in fact not sufficiently detailed (in terms of spatial resolution) and customized (in terms of crop characterization) to address the needs of local authorities and the private sector. At farm scale, existing monitoring systems are instead currently focused on other crop types such as wheat or high-income cultivations (e.g., vineyards and orchards). Although rice in Europe is cultivated with modern techniques and in intensive cropping systems, several researches demonstrated however that potential yield usually exceeds the actual one [34]. This gap reflects numerous deficiencies in crop management, which can be supported by agro-monitoring systems allowing a better characterization of production variability. Besides for yield maximization, these systems can aid in improving the environmental sustainability of agro-practices, which is of particular importance in the framework of recent changes in the European CAP (Comunitary Agricultural Policy) subsides system.

Due to the different needs of interested stakeholders, which range from public authorities to single farmers, two interconnected services were developed and tested in three European rice-producing countries: Italy, Greece and Spain. The first is focused on regional monitoring of crop conditions and yield forecasting, while the second on spatial variability analysis and crop modelling at farm-scale. Information generated within the two services is disseminated to end-users using state-of-the-art and user-friendly web platforms, and through a dedicated mail alerting system. Although the two services are logically separated and provide different kind of products, they also share many assets in terms of technological solutions and hardware/software resources. The system was designed following a modular approach, where core software components are re-used in either services, and is easily extensible with specific functionalities (thus improving flexibility and efficiency).

This paper gives an overall view of the ERMES system and its peculiarities. In particular, Section 2 describes the characteristics and aims of the two services and of the main data products and information generated and disseminated to the end-users, while Section 3 briefly analyses the structure of the hardware/software infrastructure created to handle data management and information dissemination. Finally, Section 4 describes some significant results obtained in the demonstration period (2015-2016), focusing on highlighting already achieved or potential real-world applications of the provided information.

II. OVERVIEW OF THE ERMES SYSTEM: STUDY AREAS, PRODUCTS AND SERVICES

In the ERMES project, several data products providing useful information for rice crop monitoring and management were developed, integrated and disseminated using dedicated software tools as two main downstream services, devoted respectively to regional- and local-scale applications. Those services were deployed and tested in three European study areas in Italy, Spain and Greece. This section provides a brief overview of these study areas, and discusses the main characteristics of ERMES products, services and information dissemination strategies.

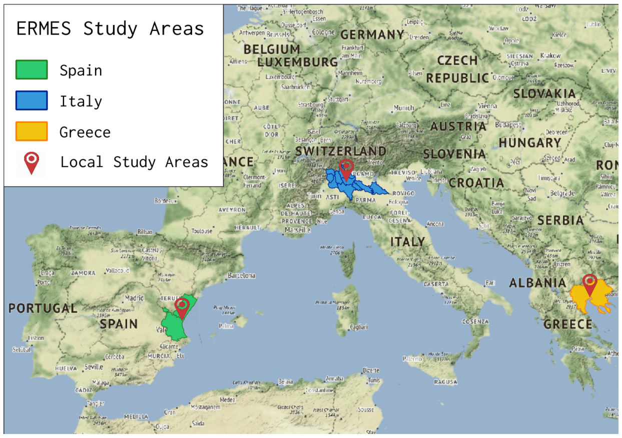


Fig. 1. ERMES Regional and Local study areas.

A. ERMES Study Areas

ERMES study areas were selected in three Mediterranean countries, responsible of about 85% of total European rice production: Italy (51.9%), Spain (26.1%) and Greece (7.0%)[35]. In each country, both a regional and a local study area were defined (Fig. 1).

- **Italy:** The regional Italian study area corresponds to the rice district of Lombardy and Piedmont, located in the Po River alluvial plain between the Provinces of Milano, Pavia, Vercelli and Novara. Rice cultivations in the area cover about 200000 ha, accounting for 90% of Italian – and 45% of European – rice production. Many different rice varieties including both *indica* and *japonica* types are cultivated within the area, spanning from very traditional long-cycle ones (e.g., Carnaroli) to the new generation of Clearfield® rice. *Long-grain type A* varieties represent almost half of the rice area (47.6%), followed by *long-grain type B* and *short-grain* (25.2 and 24%, respectively). Climate of the area is rather cold for rice cultivation. Sowing can occur from as early as beginning/mid-April to as late as the end of May for modern short-cycle varieties. Temperatures in April and in May are at the lower limits for rice germination, and cold spells can cause poor emergence problems. The hottest months of the cultivation period are usually July and August and precipitations are present in all months in levels higher than 40 mm, thus increasing the risk of rice blast infections. Flowering usually occurs at the the end of July/beginning of August, whereas the main harvesting period is between mid-September and October. Average yield is also influenced by varieties variability, and can range from around 6.0 (e.g., *Long-grain type A*) to about 6.9 ton ha^{-1}, with an average value of about 6.6 ton ha^{-1} in 2010-2014 (http://www.enterisi.it/servizi/bilanci/bilanci_fase01.aspx?Campo_15868=9).

The local study area is located in the renowned rice district of Lomellina, situated in southwestern Lombardy between the Ticino, Sesia and Po rivers. In particular, activities were focused in three farms sizing between 100 and 350 ha, particularly interested in analysing the possible benefits of RS and crop modelling for improving management practices, in particular concerning the use of nitrogen fertilizers.

- **Greece:** The regional Greek study area includes the two main rice cultivation districts of the country, Thessaloniki (18000 ha) and Serres (4000 ha), adding up to almost 75% of Greek rice-cultivated surface. *Indica* and *japonica* varieties account for around 66 and 34% of cultivated area, respectively, with long-grain type B types being the most commonly cultivated (around 66%), followed by medium-grain and long-grain type A. Climate of the area is particularly suited for rice cultivation in terms of temperatures (particularly in the Thessaloniki area), with the main constraints limiting rice cultivation expansion being soil salinity and possible irrigation water shortages. Sowing usually occurs at the end of May, with flowering at the beginning of August. Harvesting can span from the end of September to early November depending on precipitations in the last two months. Rice cultivation in Greece is very intensive and highly mechanized, especially in the region of Central Macedonia. This, in combination with the favourable climate, leads to average yields among the highest in the whole world, especially in the area of Thessaloniki where they reach averages of around 8.7 ton ha^{-1} (data provided by the Greek Ministry of Rural Development and Food, 2015). The main local case study area refers to an experimental rice farm of about 50 ha managed by ERMES partner DEMETER (Institute of Plant Breeding and Genetic Resources of the Hellenic Agricultural Organization) in the municipality of Kalochori (south-west of Thessaloniki). In addition, many other local farmers from Kalochori participated in project activities, by providing information and benefiting from demonstration of ERMES results.
- **Spain:** The regional Spanish study area is situated at the east Mediterranean coast, and comprises two of the largest rice districts of Spain, namely the Natural Park of Albufera (nearby Valencia), and the Ebro river delta, adding up to about 35700 ha of rice cultivated area (about 33% of total Spanish rice area). *Japonica* varieties of the *short-* and *medium- grain* types are the most commonly cultivated (e.g., Senia, Gleva, Bomba). Climate of the area is well suited for rice cultivation, with favourable temperature between May and September and sufficient availability of water for irrigation throughout the summer guaranteed by closeness to the Iberian mountain range. Sowing takes place from late April until the end of May, with harvesting occurring in late September so to reduce the risk of being affected by the heavy rains typical of the fall months. Typical yield in the area has been quite constant over the last years, averaging around 7.9 ton ha^{-1} ([36]).
  The local case study area consists of selected farms of the Sueca and El Palmar municipalities, whose rice production is monitored by the Regulatory Board of Designation of Origin “Arròs de València” (CRDO), warranting that rice has been produced in accordance to tradition. The area is characterized by a very complex irrigation system, and by a strong fragmentation of land into parcels of small size, making difficult to rationalize farmers’ activities such as fertilization or agro-chemical treatments.

Within the three regional study areas, monitoring of rice production is conducted by dedicated public institutions (e.g., Ente Nazionale Risi (ENR - www.enterisi.it) and the phytosanitary service of the Lombardy Region (http://www.ersaf.lombardia.it/servizi/notizie/notizie_homepage_fitosanitario.aspx in Italy; Instituto Valenciano de Investigaciones Agrarias (IVIA - http://www.ivia.gva.es/) in Spain; Hellenic Agricultural Organization (DEMETER - http://www.elgo.gr) in Greece), who provided ERMES with information on historical yield statistics and field data concerning rice blast damage useful for products’ calibration and validation. Those institutions were involved in development and evaluation of products related to yield forecasting and biotic risk alerting.

Farmers of the three local study areas were also directly involved in ERMES activities. They both provided data related to their farms and crop practices (e.g., sowing dates, varieties, treatments, yield) useful for calibration and validation of local-scale modelling results, and tested and evaluated the usefulness of some of the ERMES products for precision agriculture applications.

B. The ERMES Regional Rice Service and its products

The ERMES Regional Rice Service (RRS) has been developed with the main objective of providing an innovative agro-monitoring system to stakeholders interested in information about the on-going rice season over large areas (i.e., regional/district scale). Its target audience includes public authorities (e.g., regions, provinces, municipalities, environmental protection agencies, etc.) with the mandate of providing official cultivated surface and yield statistics (e.g. ENR in Italy), monitoring the agricultural system, developing, supporting and implementing agro-policies, and providing information to farmers concerning potential risks of biotic/a-biotic injuries or best-practices for cultivation. Other interested entities comprise private subjects such as insurances/reinsurances companies working in the agricultural sector, traders/millers or large cooperatives of farmers, who could benefit from accurate information about the on-going season to define suitable market strategies.

The ERMES RRS focuses therefore on creating and disseminating Near Real Time (NRT) spatialized information derived from the integration of RS images, weather data and crop modelling about:

i) Surface of rice cultivated areas for the on-going season;
ii) Status of the rice season as compared to average conditions (spatial and temporal anomalies);
iii) Current and forecasted biotic risks for rice cultivations;
iv) Yield forecasts at regional level.

The main ERMES products developed for these aims are summarized in Table I, along with their data sources, main characteristics and usefulness for regional stakeholders.

C. The ERMES Local Rice Service and its products

The ERMES Local Rice Service (LRS) was developed with the main objective of providing the private sector (farmers or agro-services such as operators for variable rate technologies applications or insurance companies) with information at field/farm scale. Such information targets optimization of the cropping system (i.e., yield increase), reduction of costs, and support to monitoring/damage quantification activities. In particular, the analysis of users' requirements highlighted that one of the main topics of interest for rice farmers is the optimization of nitrogen fertilization, achievable in case information about phenological stage and nutritional status is available. Insurance companies were also found to be particularly interested in high-resolution information about within-field crop variability, which can aid their activities in damage assessment related to farmers' insurance claims.

ERMES LRS focuses therefore on integrating high spatial resolution RS data, local weather data, dedicated modelling solutions and field information provided by farmers to create added-value information concerning:

i) Constant (i.e., persisting for several years) and seasonal (i.e., observed in the on-going season) intra-field variability in rice crop status and development;
ii) Current and forecasted potential risk for rice blast infection at field scale;
iii) Crop development stage and its relationships with most suitable periods for fertilization.

The main ERMES products developed for these aims and included in the LRS are summarized in Table II, along with their data sources, main characteristics and usefulness for local stakeholders.

D. Information dissemination and collection: ERMES geoportals, mail alerts and AgriNotebook

Although adequate products suiting the needs of potential users are of utmost importance, timely and user-friendly dissemination of these products to the stakeholders is paramount to obtain truly effective downstream services. In ERMES, this is mainly achieved through the use of two geo-portals (ermes.dlsi.uji.es/), specifically developed to allow efficient access to the rice-monitoring information produced for regional and local services, respectively. A user-centered interface design, where the targeted users' characteristics and needs are taken as a starting point, was married with a strong technical analysis to balance simplicity and user-friendliness on one hand, and rich added-value information dissemination on the other. In short, information is served to users in the form of raster maps relative to a specific product and date, and/or graphs representing the temporal changes of specific parameters of interest (e.g., Leaf Area Index (LAI), air temperature, crop development stage, etc.) on a given point or rice field. Useful additional functionality includes the possibility to compare parameters in on-going season with "average" conditions, overviewing the evolution of parameters using animated maps, and comparing data products in time and/or space.

Besides the local and regional geoportals, which require an "active" intervention (i.e., pull-based) and whose use may still be challenging for technologically illiterate actors, information derived from selected ERMES local data products is also directly pushed to users using an automatized and personalized mail alert system. This is the case of local data products related to blast risk and crop development stage monitoring at field scale, which are used to trigger alert mails under specific conditions (i.e., in the case of occurrence of forecasted high blast risk periods, or when the best periods for nitrogen fertilization periods are being reached). This "push-based" communication allows for a more direct and faster interaction with farmers, and is particularly important when information is useful only for a narrow span of time, as it is the case of data aimed to support specific agro-practices.

To be accurate, this type of personalized dedicated service requires very detailed information about cultivation practices on a per-field level. To obtain such fine-grained, field-level information, which is only available to the farmers themselves, we developed a dedicated web-based and mobile application (AgriNotebook). AgriNotebook allows farmers to record their agricultural managerial practices (using the web-based variant) and report in-situ information (using the native mobile variant), thus allowing farmers or field operators to record geo-tagged information about cultivation practices (e.g., sowing date, variety, fertilization and pest-control treatments) and occurrence of particular problems (e.g., weeds infestations, pest attacks). Farmers benefit from the possibility to overview and visualize all relevant information regarding their cultivation workflow (i.e. replacing the traditional "field notebook"), to export recorded data (e.g., for legally mandatory reporting practices), and to obtain more accurate, added-value information for decision support from ERMES modelling solutions.

From the above, it becomes clear that to work operationally, the ERMES downstream services require a robust yet flexible underlying (software and hardware) architecture allowing to *i)* retrieve, transform and process a variety of heterogeneous data sources (e.g., RS data, weather data, user-provided structured and unstructured data) made available by different means (e.g., FTP (File Transfer Protocol) download, public API's (Application

Programming Interfaces), database querying, AgriNotebook), *ii)* run crop-modelling simulations, *iii)* manage, store and serve the resulting data and data products, *iv)* disseminate timely and crop-relevant information through pull-based visualization (geoportals) and push-based notification (e-mail alerts). Due to the volume of data involved, and the computational cost of (some of the) transformation and processing at hand, the architecture has to be highly scalable and distributable. Finally, due to the time-sensitivity of (some) data products, a high degree of automation throughout the workflow from raw data to information dissemination is fundamental. The overall architecture of the system designed with this aim is described in the next section.

III. OVERALL ARCHITECTURE OF THE SYSTEM: BRIDGING THE GAP FROM DATA TO INFORMATION

The ERMES system can be conceptually subdivided into four sub-systems: *i)* "Data gathering and products generation", *ii)* "Data Management", *iii)* "Crop Modelling" and *iv)* "Information dissemination and user interaction" (Fig. 2). These sub-systems are heavily interconnected, and communication between them occurs through a collection of Application Programming Interfaces (APIs) and services. This allows components within each sub-system to be technology- and implementation-independent, easily interchangeable, and supports a variety of end-user applications to be built on top of them. In addition, scripting plays a crucial role in automating the I/O flows leading to data/information deployment, hereby reducing human intervention to a minimum. These characteristics are of fundamental importance in the framework of downstream services dedicated to the agriculture sector, for which quick information deployment during the growing season is of utmost importance, and requests for custom, dedicated tools for specialized applications are common. The four sub-systems of the ERMES architecture and their connections are briefly described hereafter.

A. *Data gathering and products' generation*

This sub-system is a collection of individual components each of which gathers the necessary input data and generates one of the ERMES products described in Table I and II. Each component is independently developed and maintained by one of the ERMES partners, using their own hardware/software architecture and proprietary algorithms. The resulting data products are successively deployed to the Data Management and/or Crop Modelling sub-systems. This distributed approach was preferred over a centralized products' generation system for various reasons, among which *i)* the heterogeneity of ERMES data sources and output products (e.g., spatial and temporal granularity), *ii)* the different characteristics and requirements of the algorithms used to produce them (e.g., programming languages and degree of automation/required human intervention), and *iii)* the computational complexity and resource requirements of some of these algorithms. This approach also allowed algorithm developers to more easily intervene on their processing chains (e.g., for testing and problem-solving purposes), thus allowing greater and easier control on products' generation and validation.

A notable component of the data gathering and generation sub-system is the AgriNotebook application, which was developed to allow local farmers to collect data about agro-practices and managerial activities in a user-friendly and uniform way, while being at the office (desktop version) or in the field (native mobile App). AgriNotebook closely follows the cultivation workflow, and allows the farmer to record all relevant information (see Fig. 3, right, for types of data collected). Additionally, local farmers can share their observations through a mail alerting system, thus providing real-time notification of risk factors. As such, it is extremely valuable for covering all aspects and stages of the rice crop season, and its generality makes it applicable to other crop types as well. The provided detailed parcel-level information is stored in the agro-practices database for further integration with the ERMES–WARM database (Section 3.C), providing valuable information to increase the accuracy of the modelling system for simulations at local scale, and allowing visualization and overviewing of agricultural practices in the local geoportal. This also provides a "diary of agricultural tasks" made up of chronological-ordered cultivation practices and activities, which may support legally required reporting of crop cultivation practices or serve for documenting field activities.

B. *Data Management*

Most ERMES data products are deployed to a dedicated FTP file repository, which also stores ancillary datasets such as administrative units or field boundaries vector files. The file repository acts as an interface to a GeoDatabase optimized to generate the necessary geospatial services for data access, retrieval and visualization. This GeoDatabase combines an ESRI File Geodatabase and mosaics data models to provide a convenient schema for handling time-series of raster images, which is a common pattern of all ERMES data products. Once mosaics are in place, counterpart geospatial services are set up to deploy the corresponding data products on the Web as queryiable service endpoints. A series of scripts were developed to automate the data flow from the FTP file repository to mosaics datasets, and subsequently to generate the corresponding geospatial services. These scripts run periodically (nightly) and are synchronized with data product uploads, as to ensure timely delivery of new products to stakeholders. The FTP file repository is also interfaced with a dedicated on-line catalog (http://get-it.ermes-fp7space.eu/) based on GET-IT (Geoinformation Enabling ToolkIT starterkit®), which allows to discover and access available ERMES products using standard OGC requests (CSW, WMS, WCS, WFS) as implemented in common GIS software.

Finally, ERMES user-collected data about agro-practices and other information of interest is stored in a dedicated database,

TABLE I
CHARACTERISTICS OF THE MAIN PRODUCTS OF THE ERMES REGIONAL RICE SERVICE.

Product	**Input data**	**Description** ***(spatial/temporal resolutions)***	**Use and applications**	**Methodology**	**Validation**
Rice surface maps Multitemporal flooding maps	Sentinel-1/2A; Landsat OLI	Maps of rice crop extent[1]; Multitemporal maps of flooding in paddy rice fields[2] *(30 m spatial resolution; [1] once/twice per year; [2] Decadal - NRT)*	Monitoring interannual variations in rice extent monitoring irrigation practices	Multi-temporal Sigma nought rule based Rice Detection (MAPscape-RICE)[37]	Against field land-cover observations
Phenological maps *(Sowing and flowering dates)*	MODIS 250 m EVI time series	Maps of rice's sowing and flowering dates *(2×2 km grids; computed once per year about 3 weeks after sowing and after flowering)*	Highlighting anomalous conditions on rice development Inputs for crop model simulations	Phenorice algorithm [8], [38]	Against aggregated field data of sowing dates for 2 seasons
Leaf Area Index maps	Proba-V / MODIS time series	LAI maps derived from existing coarse resolution products *(2×2 km grids; Decadal – NRT)*	Highlighting anomalous conditions on rice development Inputs for crop model simulations	Reprocessing of Copernicus and MODIS products	Inter-comparison with LAI ERMES local products according to CEOS-LPV validation protocols
Meteorological maps *(T, P, RH, WS, Rad)*	TIGGE time series at 0.25° resolution	Maps of the main meteorological drivers for rice development for current day and 6-days forecasts *(2×2 km grids; Daily – NRT)*	Highlighting anomalous conditions on rice development Inputs for crop model simulations	Interpolation of ECMWF-TIGGE [39] data and calibration with MARS data	Against Ground Meteorological Stations (GMSs) close to rice fields
Potential risk for Rice blast infection	ERMES RRS Products	Maps of potential risk for rice blast infection for current day and 6-days forecasts *(2x2 km grids; Daily)*	Highlighting periods of high risk for rice blast infection due to unfavorable climate conditions	WARM model regional customized solution [40], [41]	Compared to information retrieved in grey literature or supplied by local institutions and farmers
Rice yield forecast	ERMES RRS Products	Forecasted rice yield *(Region-Rice District level; estimated twice per year at flowering and end of season)*	Providing early estimates of rice yield for the on-going/recently finished rice season	Post processing of WARM regional outputs and historical official yields [40]	Cross-validation against 2000-2013 official yield statistics

TABLE II
CHARACTERISTICS OF THE MAIN PRODUCTS OF THE ERMES LOCAL RICE SERVICE.

Product	**Input data**	**Description** *(spatial/temporal resolutions)*	**Use and applications**	**Methodology**	**Validation**
Constant pattern maps	VHR/HR archive multitemporal images	Maps of crop zones with constant behavior over several years *(2-30 m, produced only once (static layer))*	Identify areas of low growth due to soil inhomogeneity, useful to support variable-rate basal fertilization and seeding density	Hierarchical clustering based on Expectation Maximization [42]	Clustering validity indexes; ANOVA analysis wrt to vegetation vigour
Seasonal pattern maps	VHR RS images *(Rapideye, Worldview, COSMO-SkyMed (CSK))*	Maps of within-field spatial variability expressed as: 1) comparison to field average conditions, and 2) 3-classes clustering *(2-5 m, Produced in key moment of the crop cycle (e.g. emergence, tillering, panicle initiation))*	Detect crop status anomalies to support planning of variable rate nitrogen fertilization; Detect crop damage/weeds infestations	Fuzzy clustering of normalized intra-field anomalies on Vegetation Index / Backscatter maps	Comparison with field LAI measurements and destructive biomass sampling
LAI HR maps	Sentinel-2A and OLI multitemporal images	LAI maps *(30 m; Decadal)*	Highlight anomalous areas within rice fields; Provide recalibration information for crop modelling solutions	Inversion of PROSAIL Radiative Transfer Model calibrated for rice crops by machine learning techniques [43]	Comparison with field LAI measurements with different instruments and with PocketLAI smartApp
Development Stage simulation	Information provided by farmers; local weather data and forecasts; ERMES LAI maps	Simulations of development stage for current day and 6-days forecasts *(Field scale; Daily)*	Provide forecasts about crop phenological stage useful for planning top dressing fertilizations	WARM model local customized solution [40], [41]	Comparison with field LAI and biomass measurement and phenological observations
Potential risk for Rice blast infection (*Magnaporthe oryzae* B. Couch)	Information provided by farmers; local weather data and forecasts; ERMES LAI maps	Simulations of potential risk for rice blast infection for current day and 6-days forecasts *(Field scale; Daily)*	Provide forecasts about potential biotic risks useful for planning agro-chemicals treatments	WARM model local customized solution [44]	Compared to information supplied by local institutions and farmers; Grey-literature analysis

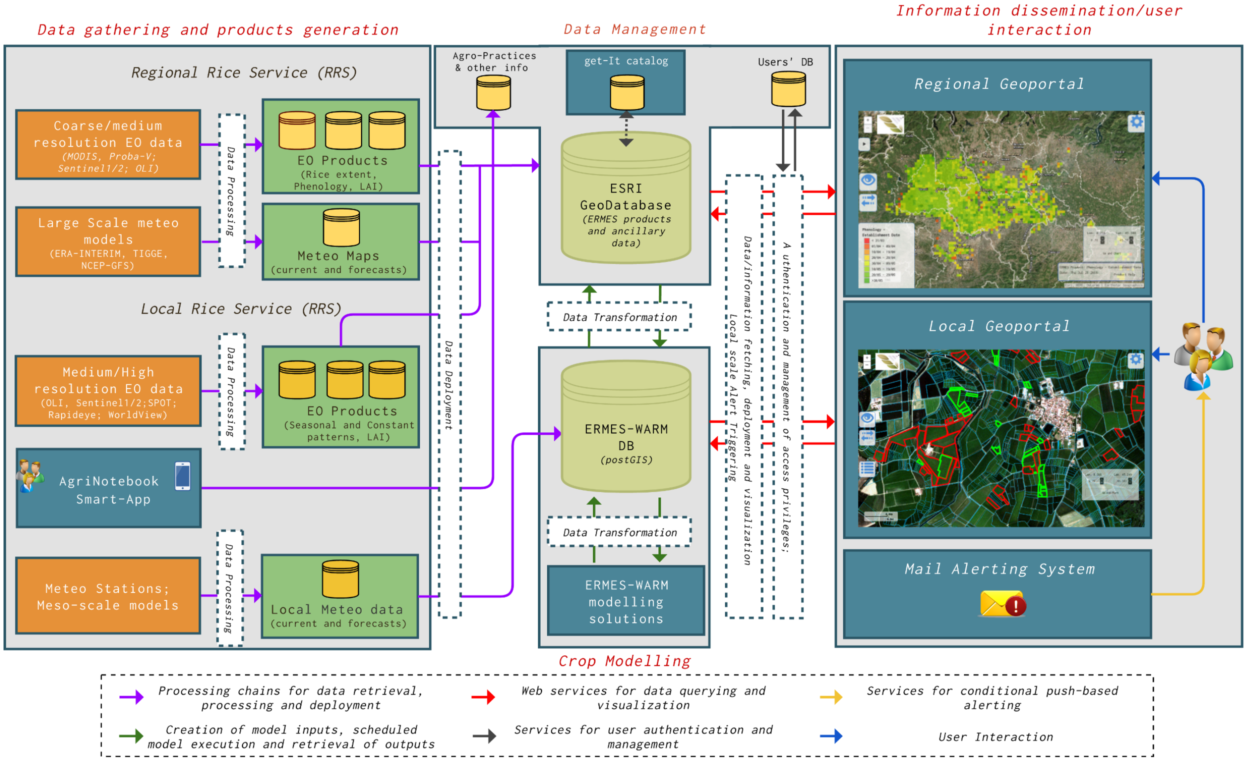


Fig. 2. Overall architecture of the ERMES system.

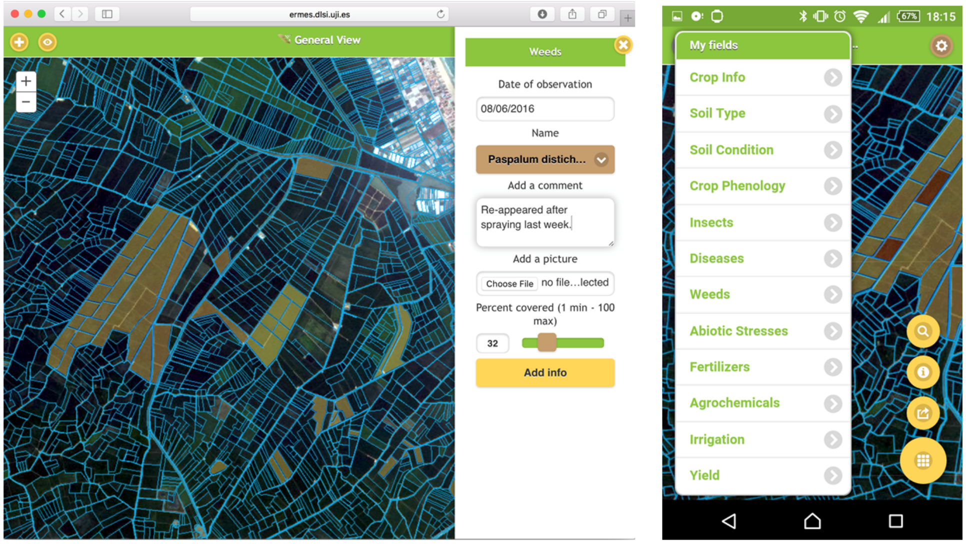
which is exposed through a Restful service-based API for data access and retrieval.

C. Crop Modelling

The core of the Crop Modelling sub-system are the ERMES-WARM regional and local rice solutions for rice modelling. These solutions are alternative customizations of the rice-specific Water Accounting Rice Model (WARM, [40]), and include algorithms for processes involved with crop growth and development, impact of biotic and abiotic stressors affecting the crop, soil water balance, impact of agro-management practices and qualitative aspects of yields ([41], [45], [44]). Differences between the two modelling solutions refer to different approaches used for the simulation of some processes (e.g., photosynthesis) and are due to the need of maximizing the coherence between the level of detail used in sub-models and the actual availability of data at different target spatial scales (regional/local). Minimum input requirements for both solutions are constituted by daily weather data (temperature, precipitations, air humidity, wind speed and radiation), information on grown variety (or variety group), and base agricultural practices (sowing date; irrigation). This information allows the model to simulate a variety of information (e.g., development stage, biomass in the different plant organs, risk for blast infection and its impact on yield, cold-induced spikelet sterility, etc.). Simulations are run daily, exploiting both past and forecasted weather data (up to 6 days), with the elementary simulation unit corresponding to the cells of a 2 km × 2 km regular grid for the RRS, and to single rice field for the LRS.

In the RRS, different ERMES EO products are used as additional spatially-distributed inputs for to reduce the uncertainty in model results (Table I). In particular, phenological maps derived from MODIS are used to initialize the sowing dates, and simulations are conducted for the most common variety groups grown in the areas. Multitemporal coarse-resolution LAI maps from tillering to flowering are assimilated in the modelling solution (through forcing and/or recalibration schemes), allowing to better simulate seasonal crop dynamics for each simulation unit. In the LRS, both sowing dates and variety are instead initialized using information provided by farmers or ERMES personnel using AgriNotebook, allowing a very accurate simulation of rice crop development for each field.

For regional yield forecasting purposes, daily outputs generated at grid cell level (i.e., 2x2 km) are aggregated at administrative level based on the percentage of crop presence in each cell. However, regional simulations are always affected by different sources of uncertainty (e.g., variety, uncertainty in sowing dates, lower accuracy of weather data), which make the direct use of modelling results for yield forecasting difficult. To reduce



Date of observation
08/06/2016
Name
Paspalum distich...
Add a comment
Re-appeared after spraying last week.
Add a picture
no file...lected
Percent covered (1 min - 100 max)
32

Fig. 3. Web-based desktop (left) and native mobile app (right) versions of AgriNotebook.

the sources of uncertainty, aggregated model outputs are used as regressors to build a multiple regression model (step wise, maximum number of regressors = 4 to avoid overfitting), using as-long-as-possible time series of official yield statistics as the dependent variable. The best-performing model resulting from analysis of the historical series is selected on the basis of leave-one-out cross-validation, and then used to predict yield for the current year (for additional details on the procedure, see [46]). .

The modelling solutions communicate with other ERMES subsystems through the ERMES-WARM DB, a dedicated postGIS data base that stores all inputs required to run the model (as derived from other ERMES products or provided by ERMES users through AgriNotebook), and all of its outputs. It interfaces with the FTP file repository through dedicated "R" scripts tasked to *i)* retrieve raster maps containing data to be used as inputs for the model (e.g., weather data, LAI time series) and store their information in fast-access tables, and *ii)* convert some specific model outputs (e.g., blast infection risk estimate for the RRS) to raster maps, and transfer them to the file repository for deployment. Execution of these scripts is triggered whenever a new dataset is discovered within the repository, or at the end of a model run, thus ensuring synchronization of inputs and outputs.

D. Information Dissemination and user interaction

Within the ERMES system, a wide variety of spatial and temporal data products and information, at different levels of granularity, is generated: ERMES satellite-derived data products stored in the GeoDatabase, in-situ collected user-generated data stored in the Agro-Practices database and crop modeling results stored in the ERMES-WARM database. To efficiently integrate and disseminate this information to different local and regional stakeholders, a set of Web-based software tools was developed, whereby a user centered interface design was the driving methodology to ensure the end-users' characteristics and needs were addressed in a user-friendly way (The interface of the geoportals can be seen in Fig. 3, 4 and 6). Furthermore, for the sake of extensibility, inter-operability and re-usability, the use of Web and geospatial technology and data standards (e.g., OGC (Open Geospatial Consortium) Web Services, Restful ArcGIS Web Services) and data formats (e.g., JSON, TIF) was promoted. Two Web-based geoportals, addressing respectively local and regional stakeholders, provide pull-based access to ERMES information. They allow to retrieve, visualize, compare, interpret and interact with ERMES data products using a minimal, user-centered and user-friendly interface which ensures that all stakeholders (even those not familiar with traditional GIS-based interfaces) have access to easily understandable and useful information.

In essence, the local and regional geoportals are map-based Web applications, offering the following shared functionalities:

- *Authentication*: allows registration and authentication of registered users, allowing them access to data products regarding their region (Spain, Italy, and Greece) and scale (local or regional);
- *Visualization*: allows visualizing data products in the form of raster maps, based on a thematic and temporal selection (e.g. NDVI, January 7th). Users are also provided with a time slider control to easily analyze changes in multitemporal products. Screen-split functionalities allow comparison of different products/dates (e.g., to check the temporal evolution of a product, or to interpret the interaction between different products at the same location);
- *Data charting*: allows visualizing graphs showing time series

of a selected parameter (e.g., NDVI, LAI, air temperature), for a selected point. Long term averages of the same parameter derived from historical data are also shown, allowing easy detection of anomalies. For the case of meteo data products, one-week forecasted data are also shown and highlighted;

- *Exporting and downloading*: information visualized in the geoportal, from maps to temporal charts, can be exported as pdf files, images or CSV format (for charts). Furthermore, data products are linked to the GET-IT catalogue, through which they are available for full metadata browsing and download.

The peculiarity of the local geoportal, with respect to the regional one, is that it also provides access to user-collected in-situ data, alerts and parcel-level forecasts generated by the crop modelling solutions (e.g., blast infection risk, crop development stage), for the rice fields belonging to the authenticated user. Clicking on a parcel brings up a pop-up where the user can browse the aforementioned data in a tabbed view.

Next to pull-based access to ERMES data products provided by both geoportals, the ERMES system also offers push-based data dissemination through the Mail Alerting System. It disseminates time-critical alerts to local end-users, based on forecasts generated by the ERMES-WARM modeling solution. Concretely, the Mail Alerting System checks periodically the model's outputs related to rice blast infection risk and rice development stage, and alerts the user if critical conditions occur (Section 2.2).

From a more technical point of view, the front end of the geoportals was implemented with the ArcGIS API for JavaScript, which is an optimized Software Development Kit (SDK) for accessing and interacting with server-side ArcGIS services. Data products were conveniently exposed as an array of geospatial web services, following standards-based Restful ArcGIS/OGC interfaces. Since most data are of raster type, they were handled as tiled images for visualization. To manage and access ERMES-WARM and AgriNotebook data, custom, dedicated Restful Web services were developed using Node.JS, to ease data query and data modification operations. These services are heavily used by both geoportals to govern data retrieval, and accessed by the Mail Alerting System. This is implemented as a series of Python scripts, which exploit crop modeling results to send the alerts to local stakeholders.

IV. THE ERMES SYSTEM AT WORK: HIGHLIGHTS OF SELECTED PRODUCTS

After the design phase, the different functionalities of the ERMES services were progressively implemented to run pre-operationally during the 2015 rice growing season. This allowed presenting the ERMES products and services to end-users, in order to receive feedback for refining and tuning preliminary products, data flows and dissemination schemes. The whole system was further operationalized and tested during the 2016 European rice growing season exploiting the full suite of ERMES products and services. The next sub-sections highlight some significant products and results obtained and disseminated in the three ERMES study areas in 2015 and 2016, focusing on real-world exploitation of the provided information by ERMES end-users. More than an analysis of products quality (which is the subject of dedicated publications), this is intended to provide an overview of the different kinds of information that the ERMES system is able to provide, and their usefulness in satisfying the needs of different stakeholders.

A. Regional Rice Service: Monitoring the rice season at regional scale

As described in Section 2.2, the ERMES RRS is focused on providing information useful to monitor the development of the rice season in NRT on a regional/district scale. This can be achieved by interacting with the regional geoportal.

Examples of maps and charts that can be visualized in the regional geoportal are shown in Fig. 4, for the Greek study area, highlighting the amount and diversity of information that can be retrieved and analysed. Rice crop maps (Fig. 4a) allow understanding the spatial distribution of rice cultivations and their interannual variations. Since those maps are generated during the rice season, they allow obtaining estimates of the total area invested at rice before official statistics compiled from farmers' declarations for the CAP subsidies are available. ERMES users such as Ente Nazionale Risi in Italy were interested in assessing the contribution that this geospatial product could have in providing yearly statistics of cultivated areas to the Ministry of Agriculture and Eurostat. Potential applications of the product for CAP control is also under investigation, in particular in collaboration with the OPEKEPE Greek authority (www.opekepe.gr/english/).

Multitemporal flooding maps are important to agro-monitoring authorities to understand and monitor irrigation practices (Data not shown). This is particularly relevant in Italy, where more and more farmers are switching from broadcast seeding in water, to row seeding on dry soils both to reduce costs related to irrigation, and to simplify farming activities adopting the same sowing machineries used for winter wheat or corn. This change is developing so quickly that in some areas of Lombardy it was estimated that dry seeding increased from 30% up to 80% of the total rice cultivated area in the last 10 years [47]. These changes can lead to both positive (e.g., reduction of water needs) and negative (e.g., reduction of wet areas favorable for some animal species) effects on the environment. For example, the Regional Plant health service of Lombardy Region was particularly interested on these data and analysis, due to the potential environmental issues related to the different phytosanitary treatments permitted on dry and flooded rice fields. Estimates of sowing dates (Fig. 4b is also a fundamental information to infer cultivated variety (long or short cycle) and potential problems in the current season (e.g., delays in sowing due to adverse meteorological conditions). Charts of time series of weather parameters (air temperature, radiation,

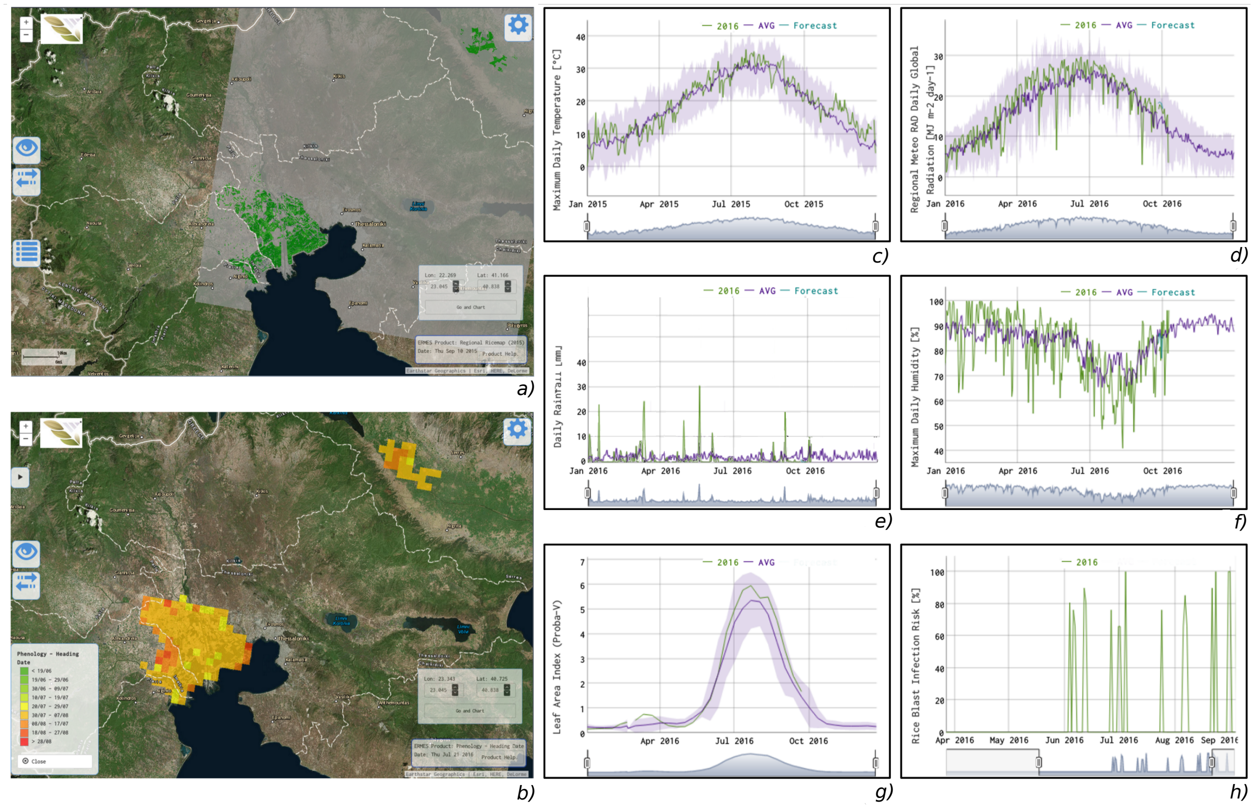


Fig. 4. Examples of information retrievable from ERMES regional geoportal concerning the 2016 growing season. *a)* rice crop map; *b)* dates of flowering; time series of *c)* maximum air temperature, *d)* solar radiation, *e)* daily rainfall, *f)* maximum relative humidity, *g)* Leaf Area Index, and *h)* simulated risk of potential rice blast infection risk. The green line corresponds to the 2016 season; the purple line is the 2003-2015 average, while the grey areas around the average (when present) correspond to the average plus or minus one standard deviation.

relative humidity and rainfall) and Leaf Area Index (Fig. 4c, d, e, f, g) allow analysts to monitor rice growth on the different areas. In particular, comparison with long-term averages allows easily highlighting anomalies in climatic conditions and/or crop status. Finally, daily simulations of potential risk of rice blast infection (Fig. 4h) allow identifying high-risk periods in the areas of interest.

In addition to visualizing and analysing them through the geoportal, ERMES products can be downloaded and used as input data for additional analysis, or as the basis for value-added services. As an example, a dedicated service was developed for the plant-health service of the Lombardy Region, to produce daily bulletins of current and forecasted rice blast infection risk aggregated at municipality scale. Those bulletins were automatically sent to technicians of the organization, and deployed on a dedicated section of its website (https://goo.gl/IszwQ4). The same information was considered useful for the private sector. ”Cattolica Assicurazioni”, one of the main Italian insurances company, provided to its clients risk information derived from RRS by SMS messages, as a support for rational use of agrochemicals and reduction of the risk of yield losses. Summarized spatial datasets derived from standard ERMES products were also used by the MARS service of the European Commission as support information for the production of their 2016 crop monitoring bulletins (https://goo.gl/j9MvYx).

When analysed on longer periods, daily blast risk estimations allow providing insights on potential production losses in a given year. For example, counting the number of days identified as being at “high risk” in the last 14 years (Fig. 5), highlights how the ERMES modelling solutions identified meteorological conditions in the 2015 growing season as particularly likely to facilitate the spreading of the disease. This was verified by the Valencian Farmers Association (AVA-Asaja), which estimated a 15% decrease in rice yield and losses of around 5.6 million € compared to previous years (https://goo.gl/W1o4q8).

Finally, RRS products are the fundamental input for the ERMES yield forecasting system, which is used to estimate rice yield on administrative units both within and immediately after the end of the cultivation season. Fig. 6 shows results obtained for three regional study areas in Greece, Spain and Italy, by comparing forecasted yields with official statistics referred to the last 12 years. The regional modelling solution was able to

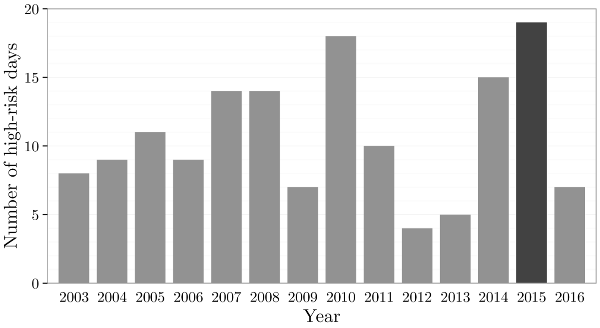


Fig. 5. Total number of days simulated as "high risk" in the June-August period in the Valencia area, for the 2003-2016 period

explain about 70% of inter-annual variability of official yields, with Mean Absolute Error in cross-validation of 0.12 (Italy), 0.20 (Spain) and 0.30 (Greece) ton ha^{-1}. The slightly worse results obtained in Greece are explained on the one hand by the higher interannual variability observed in the area, and on the other hand by the lower representativeness of the parametrization used for the Greek simulations with respect to the rice varieties grown in the area (also due to the recent increase in cultivation of high-yield varieties such as Ronaldo). These preliminary results are very encouraging in view of the development of a regional yield forecasting system.

These examples of high-level exploitation demonstrate the usefulness of the information provided and the degree of operativity of the downstream services, which were able to produce information of interest in NRT and without significant interruptions.

B. Local Rice Service: high-level spatial information as a support for agro-practices

The ERMES LRS service provides tools and information of immediate use to farmers for improving their cultivation practices, with the objective of maximizing cash inflow and minimizing environmental impact through optimization of fertilization practices and phytosanitary treatments. This information is disseminated through the local ERMES geoportal, which allows visualizing ERMES high-resolution raster maps related to intra-field crop growth anomalies (either constant or specific to the growing season) and field-scale information about crop development stage and rice blast risk derived from the ERMES local modelling solution.

Examples of maps and charts that can be visualized in the local geoportal are shown in Fig. 7. Once logged-in in the Local Geoportal, farmers can see their fields highlighted (Fig. 7a), and easily visualize ERMES products specific to those fields, as well as the information they provided through AgriNotebook. In particular, Constant and Seasonal pattern maps allow analysing the spatial variability of crop growth within a specific rice field. In particular, Constant Pattern maps, derived from analysing archives of decametric/sub-decametric of satellite images (Fig. 7b), aim at identifying problems in the field related to soils' inhomogeneity. This information is needed to support farm planning (e.g., choice of crop/varieties, crop rotation and soil movement) and to perform precision farming agro-practices such as variable-rate pre-sowing basal fertilization and sowing density.

Conversely, seasonal pattern maps highlight the intra-field spatial variability at different time points of the on-going growing season. Optical and/or Synthetic Aperture Radar (SAR) high-resolution satellite images are used to divide each field in different clusters, as a function of the relative difference between the satellite signal (e.g., Vegetation Indexes, backscatter) in the different pixels and its average value over the whole parcel. In particular, COSMO-SkyMed X-band data at 3 m resolution acquired every 8 days at the beginning of the season allowed to highlight patterns in crop emergence and tillering development. These anomaly maps - produced on a regular basis thanks to the all-weather SAR acquisitions - provide the farmers information on crop failure at the first stages of the growth cycle that can be recovered by specific intervention (Fig. 7c). CSK data is instead less useful to highlight crop status spatial variability in later periods of the rice cycle, when closing-up of the canopy makes radar backscatter rather homogeneous. To perform crop status assessment in those later stages, RapidEye (5 m spatial resolution) or Worldview (2 m) optical imagery were acquired in the most important periods for rice's top-dressing fertilization (tillering – around mid-June - and panicle initiation – around mid-July - stages). Both RapidEye and Worldview imagery provided valuable information in this context, allowing end-users to identify areas in need of higher/lower nitrogen inputs (Fig. 7d) based on analysis of Vegetation Indexes' spatial variability. Besides their lower spatial resolution, RapidEye imagery proved in particular to be a very useful data source, since it allows coverage of reasonably large areas with sufficient resolution for precision agriculture applications, and with a quite favorable price per hectare as compared to WorldView.

Near real time HR LAI maps were produced using state-of-the-art machine learning algorithms trained on simulated radiative transfer modelling data specifically generated to characterize rice features ([43]). In particular, availability of both LANDSAT OLI/ETM+ (Operational Land Imager/Enhanced Thematic Mapper) and Sentinel 2-A imagery in 2016 allowed to reconstruct a very dense temporal data set of HR LAI maps, useful to monitor crop development at field level. Anomalous drops in LAI time series can help identifying problems/damages at field level due to the effects of plant diseases or other factors (Fig. 8). Additionally, experiments aimed at using this additional information as inputs for sub-parcel crop modelling are currently undergoing. Sentinel/OLI data are instead less useful for precision agriculture applications due to the typically small size of paddy rice fields, which makes the statistical analysis of intra-parcel spatial variability difficult in many cases.

Finally, in addition to EO data, local crop modelling results

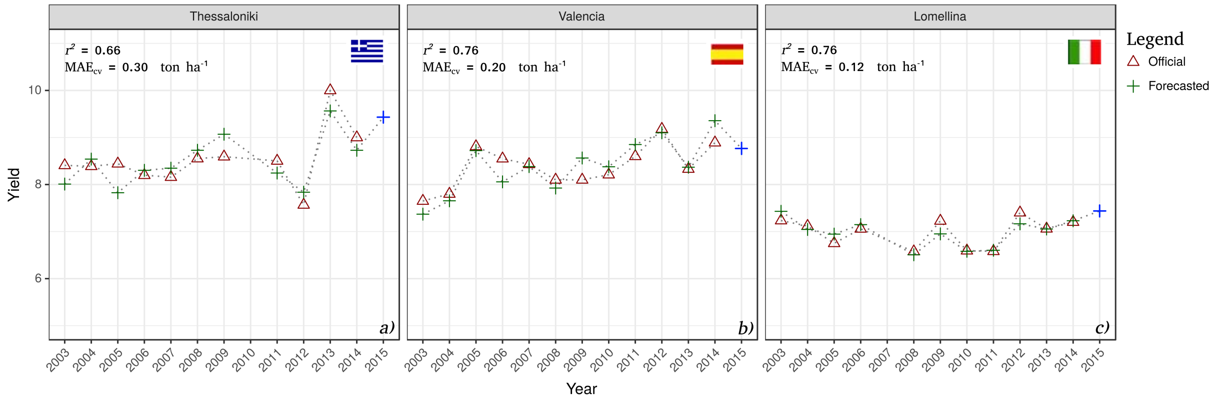


Fig. 6. Comparison between official (orange circles) and forecasted (green crosses) rice yield for *a)* Indica rice in Thessaloniki, *b)* Japonica rice in Valencia, *c)* Indica Lungo B in Lomellina. Blue crosses show forecasted yields for 2015

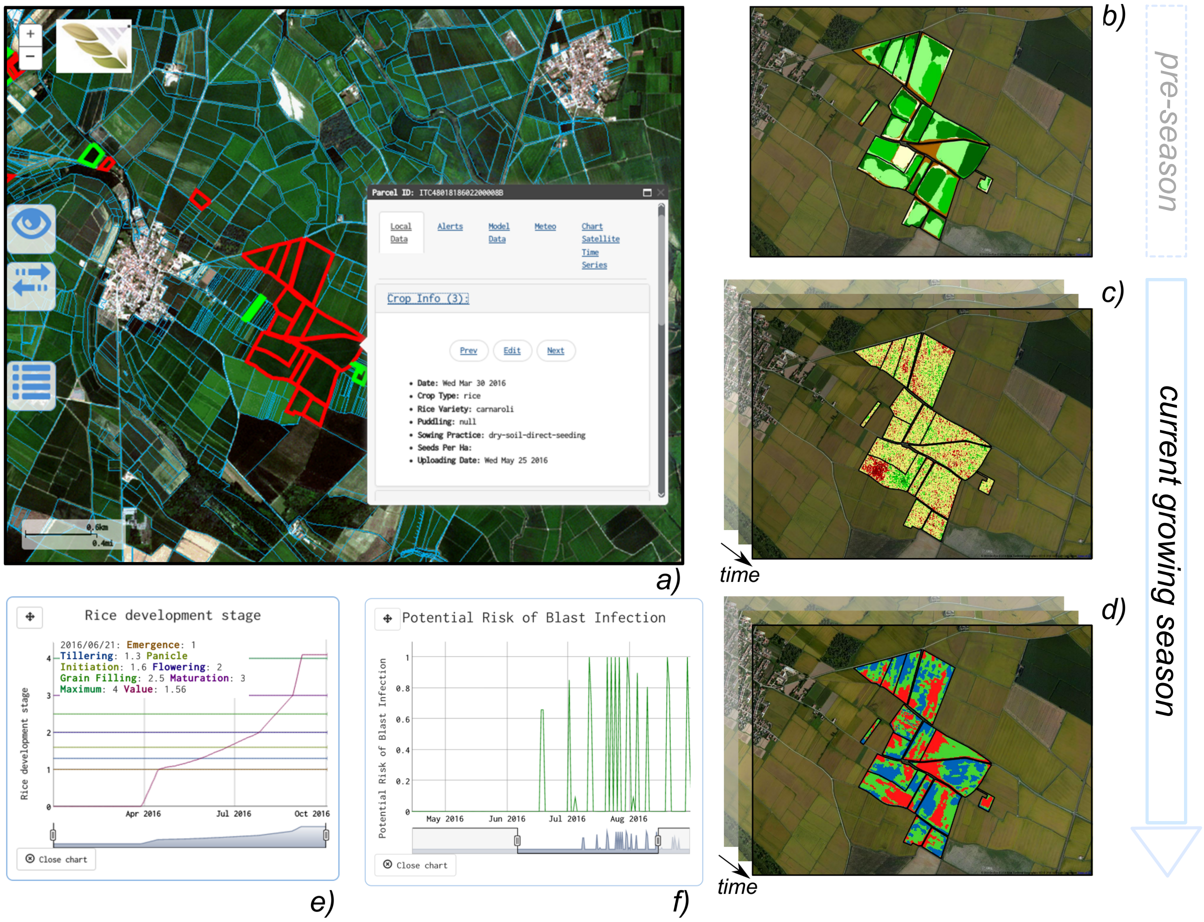
provide real time and forecasted information on rice development stage for each field (Fig. 7e), allowing farmers to properly plan fertilization/phytosanitary treatments as a function of simulated impending phenological stage. The same information was also used for triggering mail alerts when development stage approached 1.3 (tillering) and 1.6 (panicle initiation), which correspond to the best periods for top-dressing nitrogen fertilization. In addition, information on risk for rice blast infection (Fig. 7f) based on local weather data (and therefore more accurate than their "regional" counterpart) may provide support for rational application of pesticides. Since agro-chemicals treatments are currently usually scheduled on fixed calendar dates, a more ecologically (and economically) sustainable farm management can be reached exploiting this information. This is particularly true if taking into account climate-change issues, which are often out-pacing the use of agro-practices based on tradition or business-as-usual scenarios. It is for example worth mentioning that, in the three years of the ERMES project, Europe faced anomalous and extreme condition in terms of temperature, rainfall and humidity, the most evident of which was the temperature anomaly recorded in July 2015 that was the hottest period since meteorological measurements.

As in the case of the regional service, ERMES local products were also used as the building blocks for more advanced analyses and applications. A typical example is the use of the constant/seasonal pattern maps as a support for VRT treatments. Starting from intra-field variability maps, farmers in the Italian and Greek study areas, with the assistance of companies selling machinery and of ERMES personnel acting as "agri-consultant", were able to derive accurate prescription maps for nitrogen fertilization, as shown in Fig. 9(a,b). Full-field experiments conducted in 2014, 2015 and 2016 demonstrated that such prescription maps allowed a better management of field variability, leading to higher yield homogeneity and lower fertilization costs as compared to a standard fertilization scheme [48]. For example, Fig. 9c highlights the effects of adopting VRT fertilization techniques, comparing the intra-field yield variability observed in 2014 (No VRT) and 2015 (first year of VRT adoption). Although the difference in maximum yield was also due to more favorable weather conditions, the 2015 yield profile is clearly more homogeneous, and a strong increase in minimum yield can be observed. Finally, field variability maps were also used by Cattolica Assicurazioni consultants to support activities related to the assessment of crop damage (e.g., hail damage).

V. SUMMARY AND CONCLUSIONS

In this manuscript, we described the overall architecture of the downstream services devoted to rice monitoring developed in the framework of the ERMES FP7 project, and highlighted the usefulness of several of its products in providing useful information for applications related to rice monitoring at both regional and local scales. The ambitious objective of ERMES was to create an integrated system allowing to exploit information from different sources and different levels of spatial and temporal granularity (Earth Observation data, crop modelling, user-collected data), to provide information useful for various crop monitoring/management applications. This required tackling several problems, connected mostly to *i)* the development of algorithms able to retrieve useful information from the available data sources in a fast, automated (as far as possible) and reliable way, and *ii)* the creation of suitable tools for disseminating that information to different stakeholders in an easy-to-understand format and exploiting use-friendly web interfaces. The ERMES system, thanks to its modularity, allows coping well with all these issues, providing an amount of data products and NRT information concerning rice cultivations, which is as far as we know unprecedented within a single, unified platform.

The system was operationally tested during 2015 and 2016, demonstrating its robustness and flexibility in coping with unforeseen situations thanks to the redundant and complementary nature



Parcel ID: ITC4801818602200008B

- **Date:** Wed Mar 30 2016
- **Crop Type:** rice
- **Rice Variety:** carnaroli
- **Puddling:** null
- **Sowing Practice:** dry-soil-direct-seeding
- **Seeds Per Ha:**
- **Uploading Date:** Wed May 25 2016

2016/06/21: **Emergence**: 1 **Tillering**: 1.3 **Panicle Initiation**: 1.6 **Flowering**: 2 **Grain Filling**: 2.5 **Maturation**: 3 **Maximum**: 4 **Value**: 1.56

Fig. 7. Examples of information retrievable from ERMES local geoportal. *a)* Interface of the local geoportal, with rice fields belonging to the user highlighted (red ones correspond to fields with active alerts), and interface for visualization of information supplemented via *AgriNotebook* shown. *b)* Constant Pattern map for a farm in the Italian local study area (in the map, different colors correspond to different clusters identified in each field as a function of soil and biomass persistent patterns). Seasonal pattern maps from *c)* Cosmo-SkyMed (CSK) at 3 m resolution for 03/04/2016 (different colors are linked to anomalies in backscatter signal with respect to the field average), and *d* RapidEye for 14/06/2016 (red, green and blue colors correspnd respectively to below-average, average and above-average status). For each of its fields, the user can also visualize time series of simulated Crop Development Stage *(e)*, and rice blast infection risk *(f)*

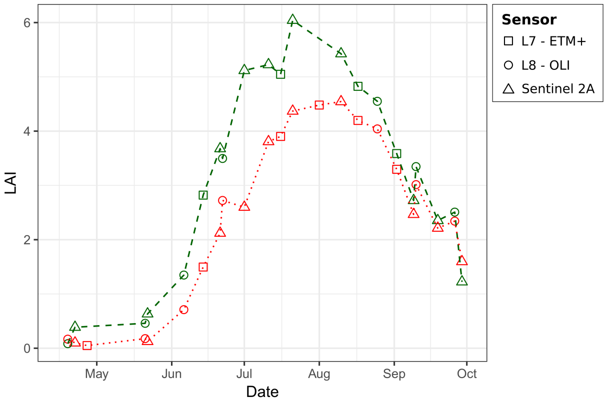


Fig. 8. Average LAI time series derived from Sentinel-2A and Landsat 7/8 data for two fields of the Italian local study area with the same sowing date and rice variety. The red line corresponds to a field damaged by an incorrect herbicide treatment.

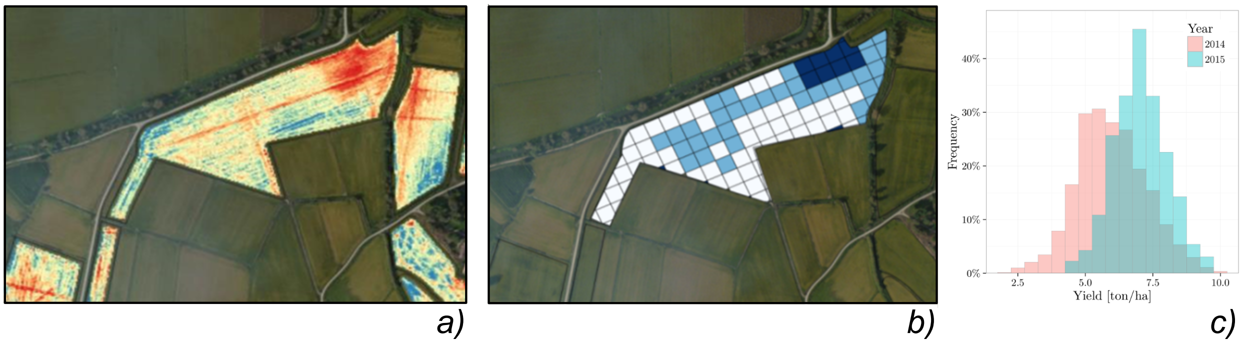


Fig. 9. Examples of *a)* ERMES field variability products (red colours correspond to lower crop vigour), *b)* prescription maps derived from their analysis (darker blue corresponds to higher nitrogen amount to be provided), and *c)* comparison between frequency distribution of final yield in the field between 2014 and 2015

of its data sources (VHR images from SAR and optical sensors) and products (e.g. operation LAI; meteo maps). The usefulness of ERMES services was demonstrated by the great involvement of different ERMES end-users and stakeholders, including public authorities, insurance/reinsurance companies, and single farmers or consortia. ERMES services were used both as a platform to perform expert-based crop monitoring, and as the basis for producing customized added-value information, such as biotic risk and yield forecast bulletins, NRT flood maps, or prescription maps for VRT Nitrogen fertilization. This kind of high-level exploitation reveals the maturity of integrated EO and crop-modelling systems, strengthened by in-situ user-collected data, as a support for agro-monitoring at different scales.

Although now nearing its end, the experience of the ERMES project in developing value-added services for agriculture will not be wasted. In fact, several stakeholders already manifested interest in providing funding to maintain and further improve some of the services' main functionalities, in particular for what concerns biotic risks simulation and alerting (on the regional side), and NRT mapping of intra-field variability (on the local side).

This further suggests that the market is starting to be mature for the development of services for the agriculture sector supported by high-level scientific evidence, if information is conveyed to interested stakeholders in a timely and user-friendly way. The adoption of monitoring systems similar to ERMES could be also be facilitated by the 2003 reform of the EU Common Agricultural Policy, which re-routed a significant portion of EU subsidies for agriculture towards sustaining innovative and more environmentally sustainable agricultural practices. These changes are targeting to lead the European agricultural sector towards production of high quality and environmentally friendly goods, and will undoubtedly aid the adoption of innovative crop management systems.

Finally, although ERMES was mainly focused on European agriculture (and specifically on rice), its methods and technologies can be also exploited for other crops and in other areas of the world. In particular, the regional system can be proposed as a country-level monitoring system in developing countries, where accurate information on crop status and dynamics are even more needed due to food-security issues. Indeed, the ERMES consortium already started collateral activities in West Africa to demonstrate the feasibility and usefulness of the ERMES RRS for crop mapping and real time monitoring of crop status.

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