ENG

Phytosanitary decisions: from calendar-based treatments to decision support systems

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The Journal of Plant Pathology was founded in 1892, as one of the first journals in the world dedicated to plant diseases. The journal's aim was "to illustrate plant parasites, the diseases they cause, and to bring to practical application, not only this knowledge, but also effective methods to appropriately control these parasites." However, the birth of plant protection as a discipline can be placed in the post-war period. A key figure in this field was the German chemist Paul Hermann Müller (Olten 1899 – Basel 1965), who was commissioned by the Geigy company in Basel to develop insecticides for agriculture. He directed his research towards chemically stable and lipophilic products and, in 1939, discovered the insecticidal properties of DDT (dichlorodiphenyltrichloroethane), a discovery that earned him the Nobel Prize in 1948.

In the 1960s, crop protection against harmful organisms (particularly fungi, bacteria, and phytophagous arthropods) was based on the use of chemical products applied according to a fixed schedule (calendar-based treatments). This was a precautionary or preventive defence method, planned with treatments at predetermined time intervals, regardless of the progress of infestations or epidemics, or the presence of conditions favourable to the development of harmful organisms. For the first treatment of the season, reference was usually made to the phenological stage at which the crop became susceptible. After the initial treatment, subsequent applications were carried out based on the persistence of the products used. Alternatively, and taking into account the synchronisation of the plant's life cycle with that of harmful organisms, protection was timed according to the phenological phases of the cultivated plants. For example, regardless of the date and the context, the phases for applying calendar-based treatments in an orchard could include bud swelling, flowering or fruit setting, the beginning of fruit growth, veraison, leaf fall, and dormancy. The underlying assumption was that the crop needed to be protected preventively during the phenological stages vulnerable to possible attacks, and this protection had to cover the entire duration of the susceptible phase.

Nevertheless, even at that time, significant initiatives were promoting a more rational approach. For example, in November 1956, a meeting open to technicians and farmers was held at the University of Bologna, where the results of a collaborative experiment on grapevine downy mildew control were presented. Specifically, biological and epidemiological insights into *Plasmopara viticola* were discussed, allowing for a more targeted disease management approach based on the "rule of three tens" and the calculation of the probable incubation period.

Calendar-based treatments were easy to understand and apply, even for those with limited knowledge of agricultural systems and their complexities. During the 1960s and 1970s, posters and brochures detailing intervention plans for specific plant species and pests, with guidance on treatments to be carried out at each phenological stage, were widely used among professionals. These materials were also displayed and distributed free of charge at plant protection product sales centres. These aspects (simplicity and practicality) should not be underestimated today. It is important to consider that much of the knowledge in this field developed only in later years and that technical assistance and agricultural extension services only began to be properly organised from the mid-1970s onwards.

However, calendar-based treatments led to widespread, and often unjustified, use of chemical products, with the well-known negative effects on human health and the environment. These concerns prompted public authorities to promote a more rational and environmentally respectful approach to plant protection.

From the mid-1970s onwards, the concept of guided control began to gain traction, eventually becoming the focus of the "Piano nazionale di lotta guidata", launched in 1987. The term "guided control" referred to a crop protection system in which phytosanitary treatments were not applied at fixed intervals but only when their necessity was established. While calendar-based treatments were independent of the actual presence of the harmful organism, guided control relied on in-field monitoring to confirm its presence at levels that may justify a measure for protection.

In guided control, interventions for controlling phytophagous pests were often based on exceeding intervention thresholds—levels of population density or damage severity beyond which insecticide (or acaricide) treatment was justified. These thresholds became economic thresholds when the damage caused by the pests exceeded the cost of treatment. Intervention thresholds were determined through periodic field observations and sampling, which allowed for the assessment of the actual population density of the pest and/or the extent of damage to plant organs. Field monitoring made extensive use of various types of traps (sex pheromone, coloured, food-based, etc.) to capture phytophagous pests. For plant diseases, intervention thresholds were based on the density of the pathogen inoculum (e.g., through soil sampling and analysis for soil-borne pathogens or the use of spore traps for airborne fungal spores) or on the presence and severity of the disease in the field, determined through sampling plans and symptom severity assessments on plant organs. Monitoring methods for plant diseases were more complex and costly than those for pest infestations and often provided too late responses for timely intervention. For this reason, in supervised control, interventions were frequently based on the presence of environmental conditions favourable to pathogen development. This approach encouraged the use of weather stations and agro-meteorological data, as well as the development of mathematical models and predictive rules to assess phytosanitary risk, as will be further described.

From the early 1990s, guided control became an integral part of integrated pest management (IPM) and later of integrated production, with the implementation of agri-environmental programmes and the subsequent establishment of the National System for Integrated Production Quality (Ministerial Decree No. 2722 of 17 April 2008). According to Legislative Decree No. 194 of 17 March 1995, IPM was defined as “the rational application of a combination of biological, biotechnological, chemical, cultural, or plant breeding measures, aimed at minimising the use of plant protection products containing chemical substances, to keep pests below levels that cause economically unacceptable damage or losses.”

The European Directive 128/2009 established a framework for community action to ensure the sustainable use of plant protection products, reducing their risks and impacts on human health and the environment while promoting IPM and alternative approaches or techniques, including non-chemical alternatives to plant protection products (art. 1). Article 3 of the Directive defines IPM as “the careful consideration of all available plant protection methods and the subsequent integration of appropriate measures to discourage the development of harmful organism populations, keeping the use of plant protection products and other interventions at levels justified in economic and ecological terms, and reducing or minimising risks to human health and the environment.” Under Article 14, the Directive made IPM mandatory across the European Union from 2014 and defined its key principles, which were then incorporated into Italian regulations through the National Action Plan (PAN), adopted by Interministerial Decree in January 2014.

Within the scope of this chapter, the key aspects of the Directive and the PAN include the monitoring of harmful organisms using appropriate methods and tools, which should include field observations as well as scientifically validated early warning, forecasting, and diagnotic systems, along with expert consultation. Based on monitoring results, professional users decide whether and when to apply plant protection measures. Scientifically reliable and validated threshold values are essential for decision-making.

More recently, the European Green Deal has introduced a series of proposals to transform EU policies on climate, energy, transport, and taxation, aiming to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. The Green Deal seeks to cut the use of plant protection products by 50% by 2030.

2. Technical assistance in support of phytosanitary decision-making

Technical assistance for the agricultural sector has a long tradition in Italy, dating back to the establishment of “cattedre ambulanti” in agriculture in the second half of the 19th century. These were created to disseminate and apply agronomic knowledge to the rural world.

According to a critical analysis published by Nardone and Zanni in Agriregionieuropa (September 2008), agricultural assistance has since undergone various developments, not always positive. In 1935, the Cattedre were transformed into provincial agricultural inspectorates, ceasing to be local initiatives and instead becoming ministerial executive offices. With this centralisation, bureaucratic duties took precedence over field assistance. The alternation between decentralisation and centralisation continued after World War II, with initiatives linked to land reform and the Cassa del Mezzogiorno. Although these initiatives began with strong intentions, they soon became primarily concerned with bureaucratic procedures. A new impetus for agricultural development came with the establishment of regional authorities and the intensification of European Community interventions, which—thanks to substantial financial efforts—contributed to the rapid spread of integrated pest management (IPM).

It became clear that the transition from calendar-based protection to guided control and later integrated protection required a higher level of knowledge and expertise, which farmers did not always possess. For this reason, the adoption of these techniques was accompanied by technical support, which evolved over time from direct to indirect assistance. This shift progressively relied more on new Information and Communication Technologies (ICT).

2.1 Direct Technical Assistance to Farms

In the 1980s and 1990s, technical assistance was structured through regular farm visits, often on weekly basis, during which the technician was responsible for monitoring and guiding the farm towards the best phytosanitary solutions. This technical support was provided by regional authorities (through agricultural development services, phytosanitary services, or affiliated agencies) via a district-level coordination body responsible for dissemination and technical assistance. For instance, in Emilia-Romagna, approximately 150 technicians were actively supporting around 15.000 hectares of agricultural production. During this period, technical assistance was also strongly backed by public investments in technician training, research, and development on key phytosanitary topics. It was during this time that the role of the specialised agricultural extension officer was established. Thanks to European Community interventions, these professionals received structured training through programmes organised by CIFDA (Consorzi Interregionali per la Formazione dei Divulgatori Agricoli), which trained over 2.000 extension officers during those years.

This model of technical assistance was based on a push approach to information dissemination, in which knowledge was directly transferred from the holder (the technician) to the recipient (the farmer). At that time, the technician also played a crucial role in educating farmers and demonstrating the benefits of guided/integrated control over calendar-based tecnique. The ultimate goal was to progressively enable farmers to adopt new techniques independently and make proper phytosanitary decisions.

2.2. Indirect Technical Assistance and Warning Services

From the 1990s onwards, the increasing number of farms practising integrated pest management made it difficult to sustain a system of assistance based on farm visits. Continuing with the Emilia-Romagna example, the area under IPM expanded to 170.000 hectares between the late 1990s and the early 2000s, which would have required between 1.300 and 1.500 technicians, while only about 400 were actually available. At the same time, as European funding was progressively reduced, a significant portion of the activities supporting technical assistance declined considerably, with no alternative funding sources to ensure continuity. This challenge was addressed by strengthening the role of central coordination for technicians and their services, alongside a gradual shift from direct farmer-to-technician contact to an indirect form of technical assistance.

This model of technical assistance for IPM remains the foundation of public advisory services today and is based on two key pillars: Integrated Production Guidelines (IPGs) and phytosanitary bulletins. Integrated Production Guidelines provide detailed and annually updated information on the key decision-making elements related to integrated crop management, including pest, disease, and weed control. The IPGs contain general principles (recommendations and requirements) for crop protection, but they do not take into account seasonal variations. As a result, their guidelines can be somewhat generic and open to subjective interpretation. IPGs often include statements such as "apply treatments when favourable conditions occur" or "intervene according to seasonal trends", which can be difficult to translate into precise agricultural practices. Determining whether and when meteorological conditions are conducive to the emergence and spread of a disease or pest is challenging, as these relationships are highly complex, often influenced by crop presence, and variable throughout the season.

Phytosanitary bulletins have been (and still are) a valuable tool for adapting the general principles outlined in the IPGs to specific crop and seasonal conditions. While various formats exist, these bulletins generally provide information on meteorological trends and forecasts for a given geographical area (e.g., a province), the developmental and health status of crops, the presence and spread of major pests and diseases, the phytosanitary risk level, and control recommendations, including authorised plant protection products in compliance with IPG rules. Over time, phytosanitary bulletins have been made available to farmers through various channels, including posters displayed on municipal notice boards or in farmer gathering points, local newspapers, and, eventually, the Internet. Unlike the push model of information dissemination described earlier—where knowledge is directly transferred from the expert (technician) to the recipient (farmer)—this form of technical assistance follows a pull approach. In this system, the person in need of knowledge (the farmer) actively seeks it from where the expert (technician) has made it available. Naturally, this assumes that the farmer is willing to invest time in retrieving the information provided by the technician—something that only happens if the farmer is convinced that such information is genuinely useful.

Since the 1990s, mathematical models for predicting plant diseases and pest infestations have become a fundamental component of phytosanitary bulletins, helping to identify high-risk periods for crops and enabling more precise and timely interventions. These models simulate the onset and progression of a specific disease or the development of a given pest based on meteorological data. Additionally, they can define negative prognosis periods, i.e., times when it is highly unlikely for a disease to emerge.

Between the 1990s and the early 2000s, there was significant progress in the development of modelling tools for IPM. This was reflected in various scientific events, such as the conference " Protezione delle colture: osservazioni, previsioni, decisioni " held in *Pescara* in 1993, and six editions of the "Giornate di Studio sui metodi numerici e i modelli per la difesa delle piante" (held in Sassari in 1999, Pisa in 2002, Florence in 2004, Viterbo in 2007, and Piacenza in 2009). These events attracted a strong following and ultimately led to the establishment of GRIMPP (Gruppo di Ricerca Italiano sui Modelli per la Protezione delle Piante) in 2009, bringing together experts from academia, research institutions, and regional advisory services. A report presented at the "Giornate di Studio di Piacenza" highlighted the results of a survey conducted among 21 regional institutions providing technical assistance for IPM, revealing that predictive models were in use for 21 insect pests and 12 pathogens affecting both herbaceous crops (such as cereals, sugar beet, and vegetables) and tree crops (such as citrus fruits, stone fruits, olives, pome fruits, and vines).

However, the momentum of those years gradually waned. By the time of the “Giornate di Studio di Brescia” in 2017, participation had significantly declined, despite the National Action Plan (PAN)—which had recently come into effect—mandating the Ministry of Agricultural, Food and Forestry Policies (Mipaaf) to promote initiatives for the development and application of forecasting and warning systems for plant diseases at a regional level. Specifically, the PAN required the standardisation of existing predictive models used in certain regions, the availability of model algorithms to relevant public bodies, and the validation of various models across different territorial contexts. Additionally, Regions and Autonomous Provinces were tasked with implementing actions to ensure a monitoring network for the development of major plant diseases, as well as forecasting and warning systems. To address these requirements, GRIMPP developed a comprehensive project titled “Piattaforma comune per la modellistica a supporto dell’IPM” (PiCoMod). The project's objectives were to: 1) provide public entities with a shared online platform granting access to mathematical models for diseases, pests, and weeds, along with their respective outputs; offer technical support to public entities for implementing these models in their territorial advisory and warning services. The project, which also had financial backing from Agrofarma, never materialised due to non-technical reasons.

Various operational models have been developed for issuing phytosanitary bulletins, with the Emilia-Romagna system serving as a long-standing reference model. This system relied on a network of field technicians conducting monitoring activities and using reference plots to track crop conditions and pest infestations, collaboration with the Regional Meteorological Service to obtain weather data and forecasts, and the development of a forecasting and warning system for crop pests and diseases, managed by an editorial team within the Phytosanitary Service. The system was based on more than *20* validated mathematical models tailored to the regional context, developed since the late 1980s. Initially, it used the FeCP-DSS (Ferrara Crop Protection Decision Support System), an IT tool developed in the late 1990s through collaboration between the Ferrara Administration, the Emilia-Romagna Phytosanitary Service, and the Catholic University of the Sacred Heart in Piacenza. Later, *the Phytosanitary Service* adopted its own dedicated system, *FitoSPA*, which provided daily automated updates, generated high-resolution maps (25 km^2) of pest and disease evolution, and allowed accredited users (mainly IPM technicians) to access the system independently. A key organisational feature of this system was the presence of provincial editorial teams composed of expert technicians trained in interpreting model outputs. These teams were responsible for verifying the outputs generated by FitoSPA, assessing model results based on local expertise and field observations, validating relevant forecasts, and using model outputs to produce weekly bulletins for both integrated and organic farming. This approach acknowledged that mathematical model outputs gained value when contextualised to the specific region where they were applied and when integrated with additional knowledge from expert technicians (such as farm histories, field observations, and specific monitoring data).

The FitoSPA system remains active today, and following the implementation of Directive 128, its forecasting results—while still reviewed by editorial teams—are now also accessible to a broader audience, including farmers and technicians, along with relevant explanations and additional contextual information.

2.3 Decision Support System (DSS)

By the mid-2000s – thanks to the evolution of mathematical modelling, environmental sensors, and internet-based technologies – decision support systems, or DSS, began to take shape and evolve as a model for technical assistance.

A turning point for the development of DSS was the work by Magarey et al., in 2002, which outlined the technical assistance model for the twenty-first century through a ‘super consultant’ computer system. The super consultant incorporates all the management solutions for farmers and provides all the information that helps the user make correct and timely decisions. The super consultant is accessible via the Internet; a website does not require the installation of software on the user's computer, is cost-effective, and can be easily and continuously updated, so that new knowledge gained from research can be transferred to farmers very quickly, even before being published in industry journals. The super consultant is based on strong automation and allows for both static and dynamic information to be considered: static information refers to those factors, specific to a particular crop, that do not undergo significant changes during the growing season (for example, the previous crop, soil characteristics, plant species, and cultivar); dynamic information, on the other hand, changes continuously and constitutes a flow of measurements (for example, weather data) or field observations (for example, crop monitoring results) that must be transmitted directly to the system.

DSS are therefore internet-based platforms and consist of four main components: 1) an integrated system for collecting data that characterises the crop environment (for example, data measured by weather or soil sensors, satellite or drone readings, cameras installed in the crop, monitoring activities, or insect traps, etc.); 2) the use of mathematical models for data analysis; 3) their interpretation based on expert knowledge; 4) the formulation of agronomic advice, alerts, or other information useful to the decision-making process. Figure 4 illustrates, in schematic form, the flow of data and information in a DSS. As highlighted in the figure, the flow of information from the crop environment, to the DSS, and then to the user is an endless loop; indeed, each farming operation changes the state of the crop and, therefore, influences subsequent decisions.

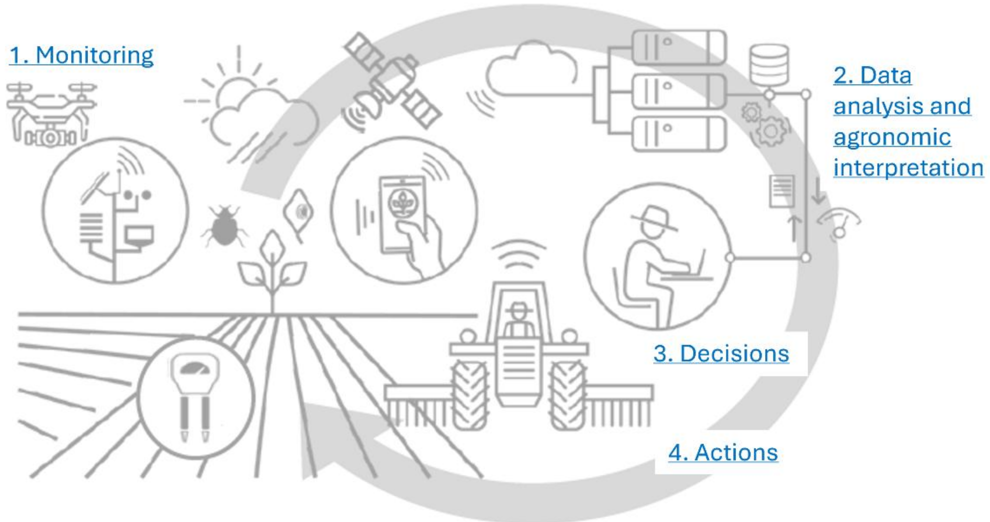

Figure 1 – A DSS (Decision Support System) is set up as an integrated system that acquires real-time data on the status of the vineyard system, analyses it through advanced mathematical models, and provides an agronomic interpretation to support decisions related to vineyard management. Actions (farming operations) change the state of the system, generating a continuous flow of information between the vineyard and the viticulturist, which improves decision-making processes and, ultimately, productive and economic results (from Caffi & Rossi, 2018, modified).

This type of DSS overcomes many limitations of the technical assistance systems described earlier. They, in fact, provide dynamic information throughout the season, with hourly or daily updates, referring to individual plots characterised by different cropping histories, varieties (including susceptibility to harmful organisms), and possibly cultivated with different techniques, including phytosanitary treatments. A DSS is aimed directly at the end user (i.e., the decision-maker) providing them with information that adds to their personal experience and helps them make correct and timely decisions for each specific cultivation situation, as required by IPM principles. A DSS combines push approaches (e.g., automatic sending of emails or SMS) and pull approaches (through a graphical interface that can provide multimedia content: icons, graphs, maps, photos, and videos). DSS do not overturn the paradigm behind the warning services described earlier – that is, that technicians and farmers are not able to directly use the outputs of mathematical models – but replace the expert intervention (the editorial structure mentioned in the previous paragraph) with automatic expert knowledge systems. DSS, therefore, make technical assistance much more accurate and timely.

The approach of other computer tools that can be defined as "plug systems" (insert the plug) is different. These systems provide end users with the output of mathematical models by physically connecting to a device installed in the field, without any agronomic or phytosanitary interpretation. The precursor of this type of tool was the AGREL station, produced in the late 1980s. These stations, installed in vineyards, collected rain and temperature data and provided, on a small screen, information on potential infection periods for *Plasmopara viticola*. Today, these plug systems have evolved technologically but not technically. They use the Internet to connect to the field data monitoring station (typically an agrometeorological station) but continue to provide raw outputs of the models, often difficult to interpret and apply by farmers.

Although DSS are primarily aimed at farmers, there are examples where warning services and DSS have created synergies. For example, Condifesa TVB (in Veneto) has developed, in recent years, BODITM (short for "bollettino fitosanitario digitale "), an innovative tool based on an application (APP) for iOS and Android devices, usable on tablets and smartphones, which informs viticulturists about agrometeorological conditions in their area, the risk of development for major diseases, and phytosanitary treatment protection. The APP is, in fact, connected to a DSS (specifically the DSS vite.net®). The consortium's technicians, thanks to their knowledge of the territory, insert representative vineyards for the various viticultural areas into the application and associate them with one of the 120 weather monitoring points. The viticulturists, using an access key, can consult real-time information on: i) the meteorological situation of the last seven days and forecasts for the following week; ii) the current and predicted phytosanitary risk levels for downy mildew, powdery mildew, botrytis, and black-rot, contextualised on environmental conditions; iii) the phenological stage of the vineyard; iv) the protection of phytosanitary treatments they have performed. After selecting the phytosanitary product from a complete product database, and entering the date and time of the intervention, the application displays the period during which the treatment will protect the vineyard from the target pathogen, in relation to the characteristics of the product used, weather conditions, and vegetation development. The system is also used – alongside other tools and mathematical models – by Condifesa TVB for the preparation of the Phytosanitary Bulletin – Agrinotizie, which is sent weekly to the viticulturists of the Treviso province via newsletter and postal service.

3. Mathematical Models

As introduced in the previous paragraph, guided control and integrated pest management have made, and continue to make, extensive use of mathematical models, whether integrated into forecasting and warning service platforms, DSS, or plug systems. Mathematical models are the heart of these systems, determining their quality and, therefore, their usefulness; if the data analysis and interpretation system is incorrect, insufficiently accurate, or inadequately tested on territories and in different cultivation and climatic contexts, then the phytosanitary advice will be wrong, as will the subsequent decisions.

The modelling for crop protection has undergone strong evolution, in which three main phases can be identified: a first pioneering phase, which dates back to the middle of the last century; a second phase, dominated by empiricism, which still persists today although with new methodologies; a third phase, with the advent of process models that have significantly increased the accuracy and robustness of mathematical models.

3.1. The Pioneering Era

Phytopathological modelling is a discipline that is more than a century old; its birth dates back to the middle of the last century, precisely to Mills' work on apple scab, where the duration of leaf wetness and the corresponding air temperature provided an infection risk. The famous 3-10 rule for the first seasonal infections of downy mildew on grapevines (Baldacci, 1947), as well as Goidanich's incubation calendar (Goidanich et al., 1957), also belong to this "pioneering" phase.

3.2. Empirical Models

Modelling for plant protection has for a long time been dominated by empiricism. In fact, to develop a model, one would start from field observations and then seek mathematical or statistical relationships that could explain the observations on the appearance or development of the disease, or the development of the pest, in relation to certain environmental variables, such as air temperature, precipitation, or the duration of humid periods. For example, the well-known model EPI-Plasmopara (short for État Potentiel d'Infection) – a model developed by Strizyk in the early 1980s in the Bordeaux viticultural area, France – provided indications on the infection risk of grapevine downy mildew through mathematical equations that, using some numerical parameters, compared the seasonal meteorological trend with the thirty-year climatic trend of the area. The well-known thermal sums used to describe the development stages of pests also fall into this category of models, as the passage of individuals from one stage to the next was expressed in degree-days (calculated using various methods) rather than in number of days. The empirical approach is still predominant today. Of course, the tools for field data analysis and the creation of mathematical rules have evolved to the present day, where the use of big data analytics and artificial intelligence is also discussed with great emphasis.

Regardless of how evolved the methods of data analysis are, the fundamental problem of empirical models remains. In short, these models take a "snapshot" of the field data used for their development, and therefore have two major limitations. The first limitation is that the "quality" of the model depends on the representativeness, quantity, and accuracy of the starting data; consequently, large amounts of data and several years of observations are required to develop a reliable model. The second limitation lies in the fact that these models are often devoid of biological significance and do not interpret the cause-and-effect relationships between environmental variables and the dynamics of epidemics or the demographics of pest populations. As a result, empirical models are generally unreliable when used in conditions different from those represented in the initial data series. The shortcomings of the empirical approach are even more important today, as due to climate change, each season is different from the previous ones, and the historical events (and climate) no longer provide a reliable reference.

For the same reasons, empirical models are transferable to different environmental and territorial realities only after appropriate validation (i.e., verification of the correspondence between the model output and the field reality) and calibration (i.e., adjustment of the calculation algorithms). The EPI-Plasmopara model mentioned earlier is a clear example of the shortcomings of the empirical approach. The model does not consider rainfall to assess the infection risk of downy mildew in the spring season, despite the fact that rain is essential for the dispersion of inoculum from the soil to the vegetation; the fact that the model was developed in a climate strongly influenced by the Atlantic Ocean, with an average of 20 rainy days and a total of 150 mm of rain in April and May, likely led the model to not perceive rainfall as "influential." As a result, the verification of the EPI-Plasmopara model in many Italian areas with different climatic conditions (from Lombardy to Veneto, Lazio to Sardinia) has produced unsatisfactory results and generated a plethora of calibration attempts, none of which led to practical use of the model in phytosanitary practice.

3.3. Process-based models

Starting from the 1990s, a different modelling approach was developed compared to the empirical one, called "mechanistic" or "process-based." This approach allows for overcoming the limitations of empirical models and developing, in a much shorter time, more informative, accurate, and reliable models. Mechanistic models are not based on the processing of field data but on the knowledge of the system to be modelled (which consists of: plant, harmful organism, and environment), the processes that regulate it, and how the system behaves in relation to external variables (mainly meteorological ones, but not only). This enables process models to provide reliable results in the most diverse cultivation and environmental conditions, including climate change.

Process models are therefore based on an analysis of the effect of environmental and cultivation variables on the various developmental stages of the harmful organism, and on how these organisms move from one stage to another through rates and within a specific time interval, according to fluxes regulated by environmental and cultivation factors. Through a detailed analysis of each single developmental stage and the factors that influence it, it is possible to develop systems of interconnected equations based on a specific relational diagram; in response to certain input data, this system provides outputs related to each stage of the harmful organism. Mechanistic models, therefore, are much more complex but far more reliable and transferable than empirical models.

Modern mechanistic models for diseases originated from the work of Vanderplank (who, in the early 1960s, expressed the development of epidemics in mathematical terms, using calculations based on financial interest rates), from the Wageningen University school in the Netherlands (which, between the late 1970s and 1980s, introduced the analysis of systems for the development of crops and pathogens), and from the group at the University of Piacenza, Italy (which, with modelling work on Cercospora leaf spot in sugar beet, between the late 1980s and early 1990s, introduced an innovative approach to phytopathological modelling).

In these models, the stages of pathogen development often represent the basic structure, where the pathogen moves from one stage to the next according to biological processes (e.g., spore germination or infection) regulated by environmental factors (primarily temperature, relative humidity, duration of leaf wetness, and rain) and cultivation factors (phenological stages and plant susceptibility). The outputs of these models allow identifying the infection risk periods during which the plant must be protected, as well as negative prognosis periods, when control interventions are not necessary. In other cases, the developmental stages refer to the host plant tissues, which, during the epidemic, move from being healthy to infected, with lesions that are first invisible (during the incubation phase), then visible (with the appearance of symptoms), infectious (with the production of new spores), and finally sterile (when the lesion no longer has the ability to produce spores and actively contribute to the disease progression). Again, the plant tissues move from one stage to the next through processes regulated by environmental conditions; the outputs of these models provide the progression of disease incidence and severity, thus allowing for the identification of intervention thresholds.

Models for pests can be phenological or demographic. Phenological models simulate the onset of various life stages of insects (e.g., egg, larva, pupa, adult), while demographic models, or population dynamics models, predict the population densities of each life stage. Phenological models are based on the fact that pests, being ectothermic, are strongly influenced by external temperatures; development is possible only within a favorable temperature range, bounded by a lower and upper thermal threshold. The response to temperature of each pest is usually determined by rearing insects under controlled environmental conditions and modelling it through specific mathematical equations (e.g., the well-known Logan function). In practice, the most widely used models are "variable delay" models (or MRV models); these simulate the development of an insect population by describing the passage of individuals through their life stages based on temperatures. MRV models take into account that individuals of the same population move through the same developmental stage at different times due to genetic, microclimatic, nutritional, etc., variability. For example, a group of eggs laid on the same day and subjected to the same temperature conditions does not hatch all at the same time but over a certain time interval; in the model, this temporal distribution is reconstructed using stochastic functions starting from a mean value and its variance. In Italy, MRV models were introduced by the University of Bologna and the Central Fruit and Vegetable Cooperative of Cesena and later carried on by the Regional Phytosanitary Service of Bologna.

Models for pest populations have very distant roots, dating back to Fibonacci's work in the early 1200s, where he mathematically described the growth of a rabbit population. Since then, the mathematical history of population dynamics has been rich with contributions, from Euler (who, in the mid-1700s, studied the geometric growth of populations and introduced the age structure of populations), to Malthus (who, at the end of the 1700s, considered food availability as an obstacle to geometric growth), to Verhulst (who, in the first half of the 1800s, introduced the logistic equation and a maximum value for population growth), to Lotka (who, in the early 1900s, studied the relationship between birth rate, age-specific mortality rates, and population growth rate using a continuous-time model), McKendrick and Kermack (who, in the early decades of the 1900s, studied deterministic epidemic models), just to name a few. In demographic models, individuals are grouped into physiological age classes, and they move from one class to another as they age; the development, fertility, and mortality rates of individuals control the population density of each class. These processes are regulated by environmental conditions (mainly temperature, but also relative humidity and photoperiod) and cultivation factors (host availability and feeding), as well as interactions with natural enemies (multitrophic models based on Lotka-Volterra predator-prey equations, known since the 1920s).

3.4 Model Validation

All mathematical models must be validated for their ability to correctly interpret biological phenomena and the dynamics of harmful organisms (biological validation); biological validation involves comparing, in a variety of cultivation situations, the model output with reality, using independent data sets (i.e., not used for the development of the model).
Another type of verification is phytosanitary validation. In this case, a defense strategy based on the use of the model is compared with the traditional one, to verify that the model can offer real advantages in the practical management of the harmful organism.

4. The use of models for crop protection

Models, and in particular process-based models, have widely demonstrated their ability to correctly simulate the biology of harmful organisms and have helped improve crop protection. By providing detailed information on the state of the harmful organism, the models anticipate the critical moments for its control (e.g., the infectious periods of pathogens or the reaching of harmful stages of pests), the likely appearance periods of disease symptoms or pests, the achievement of intervention thresholds. Models (especially when integrated within DSS) have enabled the optimization of monitoring activities in the field and the scheduling of defense interventions, both in terms of timing and the type of products to be used for each specific intervention. This has led to an improvement in defense effectiveness and a reduction in the number of treatments, which in various cases has ranged from 30% to over 50%, with evident and proven benefits from an economic, environmental, and social sustainability perspective.

Process models, encompassing the most up-to-date knowledge on the biology and ecology of harmful organisms, have also helped revisit some past paradigms about phytopathological and entomological dynamics, thus allowing for the formulation of more rational defense strategies. For example, in viticulture, the central role of oospore infections in the development of downy mildew, attention to ascospore infections of powdery mildew, and the importance of their control, as well as the reassessment of the period around flowering for the control of gray mold, are all innovative aspects that, after initial "resistance" from the operational world tied to a traditional approach, have become part of the knowledge of more skilled technicians and the practice of cutting-edge companies.

In addition to models for harmful organisms, other models have been developed over time that, when combined with the former, can contribute to improving phytosanitary decisions. These include models for plant development and growth, which can help anticipate periods of increased susceptibility to various harmful organisms and the damage they cause, as well as fungicide activity models. These models take into account the PMoA (Physical Mode of Action) of fungicides, particularly the type of activity (preventive, curative, and eradicative) and its duration over time, rainfastness (i.e., the time required between treatment and rain for the product to remain effective), tenacity (or resistance to washing), and product dilution with plant growth. These models provide information on the dynamics of protection offered by a fungicide treatment in relation to the characteristics of the fungicide, application dose, plant growth, and meteorological conditions. They can answer the following question: "I treated with a certain fungicide a few days ago, and an infectious period is expected soon; is the vegetation already sufficiently protected, or is another intervention needed?"

Models useful for biological control of harmful organisms have also been developed. In entomology, multitrophic models have long allowed an understanding of the dynamics of complex systems that include natural antagonists of pests. In plant pathology, modeling of microorganisms for biological control is more recent. These models consider the ecological needs of biocontrol agents (in terms of response to weather conditions) and their interactions with the target pathogen. This new generation of models has been developed, for example, for the biological control of gray mold in vineyards and for the hyperparasite fungus of *Erysiphe necator*, *Ampelomyces quisqualis*. In the first case, once the need for a treatment against *Botrytis cinerea* has been determined, models help choose the microbial product most likely to succeed based on the phenological phase of the grapevine and, therefore, the target organ (inflorescences for preventing latent infections, flower residues for containing fungal colonization and inoculum production, berries during maturation) and the environmental conditions at the time of treatment and in the following days. In the second case, the model helps define the optimal moment for applying *A. quisqualis*, with the goal of reducing the overwintering inoculum production of powdery mildew. These "extinctive" applications are effective when made during the early stages of development of the overwintering organs of the pathogen (the cleistothecia, or better, casmothecia); at this time, the environmental conditions are more favorable to *A. quisqualis*, and pathogen control (through parasitization of the casmothecia) is more effective.

5. The perspectives

Mathematical models have proven to be a potentially very useful tool for improving disease and pest management strategies in agricultural crops. Their use has indeed led, in many cases, to better timing of treatments, resulting in greater efficacy and a reduction in the number of interventions. The limited reliability and robustness of various empirical models, which have been used in the past but unfortunately still today in warning services, plug systems, and also in various DSS, have been a brake, if not an obstacle, to the spread of mathematical models, generating distrust and skepticism towards these tools. Nonetheless, mathematical models will continue to play an important role in the evolution of plant protection, especially within digital solutions, which are increasingly widespread both in public services and among private consultants and agricultural companies.

Digital solutions should not be seen as alternatives to technical assistance based on personal relationships between technicians and farmers, but rather as improvement tools. The technician can indeed use digital solutions to have a greater and more timely understanding of farm situations, even remotely, in order to interact with farmers more effectively, optimize farm visit schedules, and, ultimately, manage a greater number of farms. The farmer, having a greater awareness of the health status and risks to which their crops are subjected, can interact with the technician in a more participatory way, making the most of the additional expertise the technician can provide.

Just as the shift from calendar-based defense to guided and integrated defense has seen a strong commitment from public administrations, so should it be to promote the transition towards the use of digital solutions. There are indeed several obstacles to overcome. First, the presumed reluctance of the beneficiaries (both technicians and farmers), which combines objective factors such as high age and low levels of digitalization, and subjective aspects of distrust and aversion to innovation. Another obstacle, especially for small farms, is the cost of access to digital solutions. Reducing costs for farms is therefore desirable through appropriate economic aid policies that include not only the purchase of hardware but also software usage licenses. A reduction in costs is also achievable through solutions that do not rely on environmental data collected from on-site sensors, but rather on interpolated data based on farm coordinates. Agricultural meteorological data interpolation systems—especially those based on the use of radar—are increasingly reliable and can significantly contribute to the spread of digital solutions for vineyard protection.

Digital solutions are increasingly transforming into tools for the digitalization of agricultural businesses. DSS, in particular, are further evolving to provide support not only for crop protection but for the entire management of the cropping system, with functionalities for fertilization, irrigation and fertigation, soil and canopy management, and maturation and yield prediction. To this end, DSS are increasingly integrating various Agriculture 4.0 technologies to acquire an increasing amount of environmental data at shorter time intervals and with greater spatial granularity to better capture within-crop variability. They are also evolving to process prescription maps for variable rate interventions (e.g., fertilization), link actuators for the automation of crop operations (e.g., irrigation), or agricultural robots.