Phytopathologia Mediterranea (2012) 51, 3, 457−479

REVIEW

Helping farmers face the increasing complexity of decision-making for crop protection

Vittorio ROSSI[1], Tito CAFFI[1] and Francesca SALINARI[2]

[1] Istituto di Entomologia e Patologia vegetale, Università Cattolica del Sacro Cuore, Via E. Parmense 84, Piacenza, I-29122, Italy
[2] Horta Srl, Via E. Gorra 55, Piacenza, I-29122, Italy

Summary. The European Community Directive 128/2009 on the Sustainable Use of Pesticides establishes a strategy for the use of plant protection products (PPPs) in the European Community so as to reduce risks to human health and the environment. Integrated Pest Management (IPM) is a key component of this strategy, which will become mandatory in 2014. IPM is based on dynamic processes and requires decision-making at strategic, tactical, and operational levels. Relative to decision makers in conventional agricultural systems, decision makers in IPM systems require more knowledge and must deal with greater complexity. Different tools have been developed for supporting decision-making in plant disease control and include warning services, on-site devices, and decision support systems (DSSs). These decision-support tools operate at different spatial and time scales, are provided to users both by public and private sources, focus on different communication modes, and can support multiple options for delivering information to farmers. Characteristics, weaknesses, and strengths of these tools are described in this review. Also described are recently developed DSSs, which are characterised by: i) holistic treatment of crop management problems (including pests, diseases, fertilisation, canopy management and irrigation); ii) conversion of complex decision processes into simple and easy-to-understand 'decision supports'; iii) easy and rapid access through the Internet; and iv) two-way communication between users and providers that make it possible to consider context-specific information. These DSSs are easy-to-use tools that perform complex tasks efficiently and effectively. The delivery of these DSSs via the Internet increases user accessibility, allows the DSSs to be updated easily and continuously (so that new knowledge can be rapidly and efficiently provided to farmers), and allows users to maintain close contact with providers.

Key words: integrated pest management, decision-making, disease models, decision support tools, information technology.

Introduction

An important goal in modern agricultural crop production is to develop less intensive and integrated farming systems with reduced inputs of fertilizers and pesticides and reduced use of natural resources (water, soil, energy). The main objectives of these systems are to maintain crop production both in quantitative and qualitative terms, maintain or preferably improve farm income, and reduce negative environmental impacts as much as possible. Achieving all of these objectives is a prerequisite for sustainable agriculture (Geng *et al.*, 1990; Jordan and Hutcheon, 1996).

Integrated Crop Management (ICM) or Integrated Production (IP) (Boller *et al.*, 2004) and Integrated Farming (IF) (EISA, 2001) have been developed as holistic concepts that involve all crop and farming activities and that shape these activities according to the individual site and farm. These concepts have their roots in Integrated Pest Management (IPM) (Figure 1). In the middle of the last century, the appearance of broad-spectrum pesticides marked a new era of intensified agricultural production. These

---

Corresponding author: V. Rossi
Fax: + 39 0523 599256
E-mail: vittorio.rossi@unicatt.it

www.fupress.com/pm

ISSN (print): 0031-9465
ISSN (online): 1593-2095

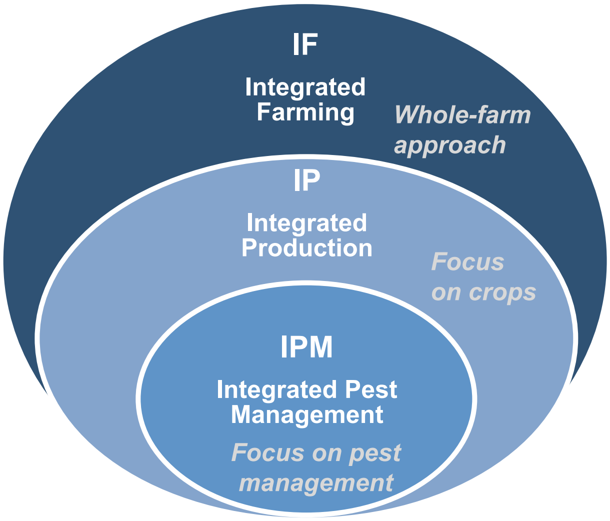

Figure 1. Integrated Pest Management (IPM) focuses on pest, disease, and weed management; IPM is part of Integrated Crop Management, which addresses all crop cultivation problems (including soil management, fertilization, irrigation), and of Integrated Farm Management, which focuses on the entire farm management cycle (including animal welfare, energy procurement, landscape management).

chemicals were powerful tools, and for a short period growers had the illusion that production could be easily increased by intensive application of chemicals that efficiently controlled pests. The disruption of the agro-ecosystems caused by massive applications of pesticides rapidly became apparent: new pests became dominant once their natural enemies were eliminated, and many resistance problems developed. To address these problems, growers intensified their use of pesticides, which increased production costs and increased the risk of pesticide residues on crops. Considerable efforts were also being undertaken by the scientific community to study pests and their antagonists, and to develop techniques for estimating arthropod numbers. It was at this time that the movement towards biological control was initiated (Baggiolini, 1990). An important milestone in this process was the foundation of the International Organization for Biological Control (IOBC) in 1956. The IOBC was responsible for coining the term Integrated Control (in 1959) and for founding the first working group for integrated control.

In the late 1970's, the concept of IPM was enlarged to include the management of the agro-ecosystem. This was an important step forward because IPM was initially limited to pest control. In viticulture, the beginning of this new era was marked by the publication of "An approach towards integrated agricultural production through integrated plant protection" in 1977 (IOBC/WPRS, 1977). In 1993, IOBC published IP definitions and general objectives, valid for all crops (El Titi *et al.*, 1993) which were then supplemented with guidelines for specific crops. For instance, the first edition of the guidelines for viticulture were published in 1996 (Schmid, 1996) and were revised in 1999 (Malavolta and Boller, 1999). In these guidelines, IP is defined as the economical production of high quality grapes, with priority given to using ecologically safer methods so as to minimise the undesirable side effects of agrochemicals and to enhance the protection of the environment and human health. Based on this short definition, IP of grapes attempts to: i) promote agricultural systems that respect the environment, that are economically viable, and that sustain the multiple social, cultural, and recreational functions of agriculture; ii) secure sustainable production of healthful, high quality food with a minimum of chemical residues; iii) protect the health of farmers while they handle Plant Protection Products (PPPs); iv) promote and maintain high biological diversity in crop ecosystems and surrounding areas; v) give priority to the use of natural regulating mechanisms; vi) preserve and promote long-term soil fertility; and vii) minimise pollution of water, soil, and air.

The Thematic Strategy on the Sustainable Use of Pesticides adopted in 2006 by the European Commission established minimum rules for the use of pesticides in the European Community so as to reduce risks to human health and the environment. A key component of this Strategy is the implementation of IPM, which will become mandatory in 2014. As stated by the Directive on the Sustainable Use of Pesticides (Art. 3): " 'integrated pest management' means careful consideration of all available plant protection methods and subsequent integration of appropriate measures that discourage the development of populations of harmful organisms and keep the use of plant protection products and other forms of intervention to levels that are economically and ecologically justified and reduce or minimise risks to human health and the environment. 'Integrated pest management' emphasises the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms".

A framework for IPM

In IPM, eight general principles are currently identified in Annex III of Directive 128/2009, even though nearly 30 elements – in addition to these eight principles – were previously mentioned in IPM material (European Commission, 2009a). A logical framework integrating these eight principles is shown in Figure 2. The core of this framework is the decision-making process. The first decisions concern the selection of measures for prevention and/or suppression of harmful organisms. The focus is on cultural practices aimed at maintaining crop health by using crop rotation, adequate cultivation techniques, and hygiene measures and by selecting varieties that are resistant to or tolerant of pests. A package of measures for growing healthy crops consists of site and crop selection, seed-bed sanitation, and attention to soil, nutrient, and water management.

A second type of decision concerns whether and when plant protection actions are required. The decision maker obtains the necessary information based on: his/her continuous monitoring of harmful organisms in the field; scientifically sound warning, forecasting, and early diagnosis systems; and the advice of qualified advisors.

When the decision is made to protect the crop, a third type of decision concerns the control measures to be adopted: if they provide satisfactory pest control, sustainable biological, physical, and other non-chemical methods must be preferred to chemical methods. If PPPs are used: i) they should be as specific as possible for the target organism and should have minimal side effects on human health, non-target organisms, and the environment; ii) they should be applied at the lowest levels that are necessary, e.g., by using reduced doses, reduced application frequency, or partial applications or by selecting

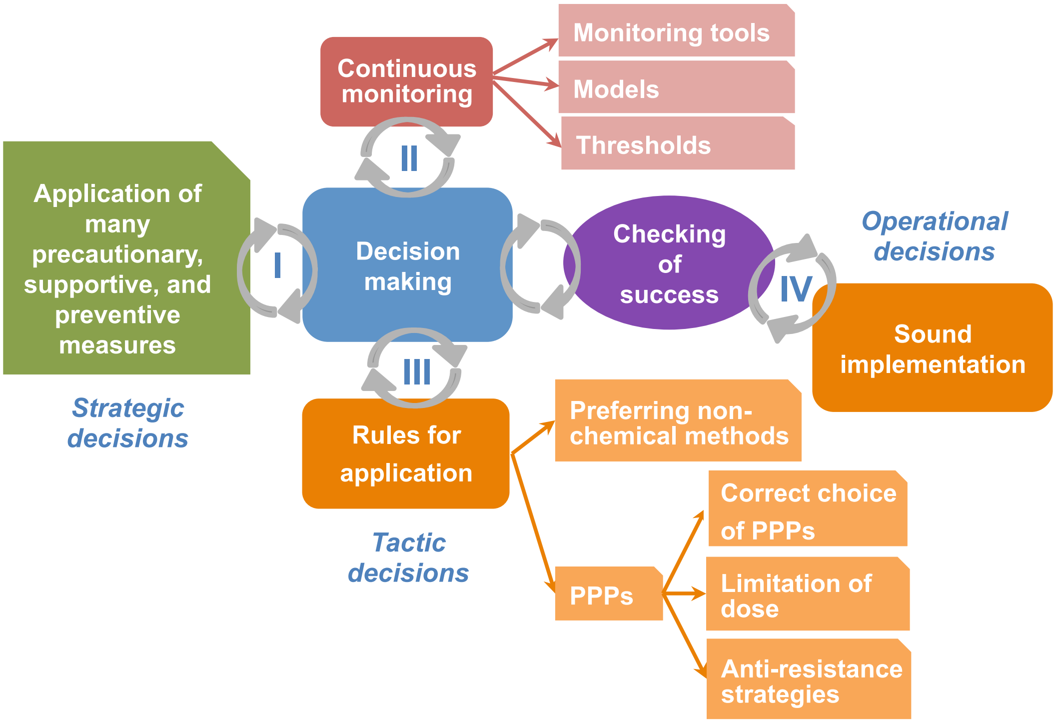

Figure 2. Framework for the implementation of IPM, based on the EU Directive on Sustainable Use of Pesticides (modified from European Commission, 2009b). The core of the framework is the decision-making process, which involves four kinds of decisions: I) strategic decisions about measures for prevention and/or suppression of harmful organisms; II) tactical decisions on whether and when to apply plant protection actions during the cropping season, based on continuous monitoring of the crop and decision-support tools; III) tactical decisions on which control measures to be adopted based on established application rules; IV) operational decisions about sound implementation of the control measures to be applied. The final step is to check the success of the decisions by evaluating their effectiveness and benefits.

PPPs that do not increase the risk for development of resistance in populations of harmful organisms; iii) available anti-resistance strategies should be applied to maintain the effectiveness of the products if the risk of resistance against a PPP is known and where the level of harmful organisms requires repeated application of PPPs (this may include the use of multiple products with different modes of action). Both alternative methods and PPPs should be accurately prepared and distributed to maximize effectiveness in controlling the target organisms and, for PPPs, to avoid both diffuse and point-source pollution.

Sound implementation of the disease management actions requires a fourth type of decision, which is made at the operational level. At the operational level, the employees who perform the management actions must select among many details concerning those actions. These include, for instance, regulation of the sprayer, operational speed of sprayer, and cleaning and maintaining the sprayer after use.

Finally, farmers and others must decide whether the previous decisions were successful, an assessment that should be based on documented evidence concerning the effectiveness and benefit of the plant protection measures that were applied. This assessment is important for learning from experiences and for guiding all subsequent interventions.

The decision-making process in IPM

IPM is based on dynamic processes and requires careful and detailed organisation and management of farm activities at strategic, tactical, and operational levels (Conway, 1984). Strategic, tactical, and operational disease management problems differ in temporal and spatial scale (Rabbinge *et al.*, 1993). Strategic decisions involve one to several years both at the farm level (e.g, crop rotation) and the crop level (e.g., the variety sown) (Figure 3); these decisions are usually made by farm owners or directors (Figure

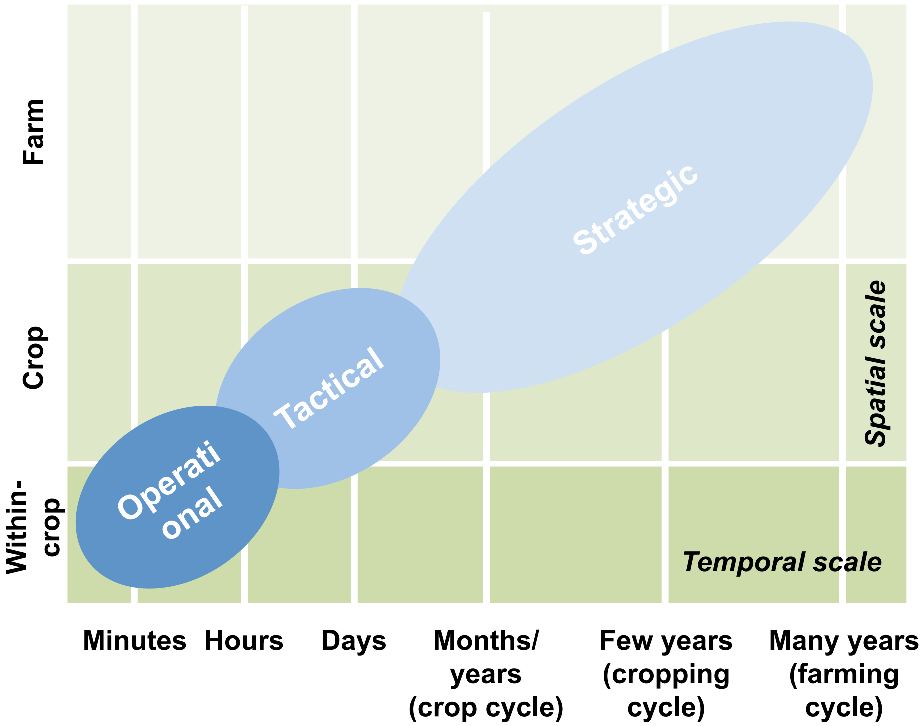

Figure 3. Spatio-temporal characterization of decision problems in crop protection (modified from Rabbinge *et al.*, 1993). Strategic decisions involve one to several years both at farming and crop levels. Tactical management decisions are made day-by-day, or within a day, in response to what is happening at the crop level. Operational decisions involve quick response to unpredicted events at the crop or within-crop levels.

4). Tactical management decisions are made by crop managers day by day, or within a day, in response to what is happening at the crop level (e.g., a disease outbreak that requires control actions). Operational decisions involve a fast response to unpredicted events at the crop level or within the crop level (e.g., the decision to postpone a PPP application because of wind) and are mainly made by the employees who implement crop protection measures.

The IPM framework in Figure 2 will work only if all the decision makers (owners, directors, employees) are in a position to select the most appropriate measures and to ensure that plant protection will be done following the IPM principles and with consideration of all possible interactions and consequences of any intervention. The aim should be to apply a system that maximises the chance of economic management of harmful organisms with the lowest risk to the user, the environment, and the public. In this context, much more knowledge is required to make decisions and the decisions are more complex with IPM than with conventional agriculture (Figure 5). In the late 1970s, farmers had to answer only two main questions in making crop protection decisions: which type of control measures to adopt and when/how frequently to implement the measures. The answers to these questions mostly depended on: i) the farmer's objectives, ii) his/her perception of past at-

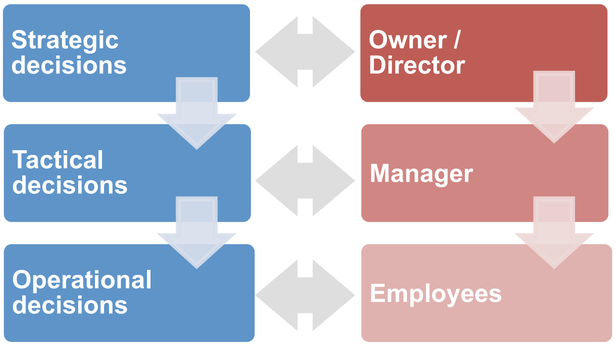

Figure 4. Strategic decisions are usually made by farm owners or directors; tactical management decisions are made by crop managers while operational decisions are mainly made by the employees responsible for the practical implementation of crop protection measures. Therefore, the IPM framework of Figure 2 will work only if all the decision makers (owners, directors, employees) are in positions to decide on the most appropriate measures (modified from Bowett, 2012).

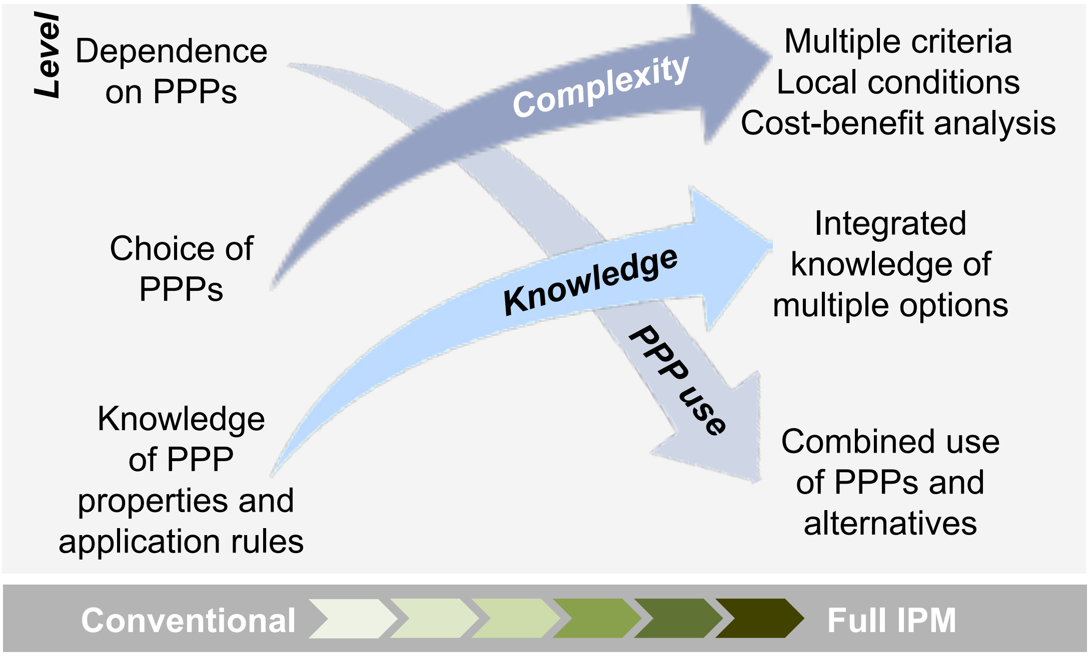

Figure 5. Implementation of IPM requires more knowledge and involves greater complexity than implementation of conventional agricultural systems.

tack and damage, iii) the control measures available, and iv) the decision rules by which he/she operated (Norton, 1976).

Compared to decision-making processes in other economic activities, decision-making processes in crop protection have received little attention (Eom and Kim, 2006). A better understanding of the decision-making process is necessary given the increased complexity of the decisions required in IPM. Decision-making is a mental process (a cognitive process) resulting in the selection of an action among several alternative solutions: every decision-making process produces a final choice (March, 1994) (Figure 6). Decision-making starts with the identification of a problem, which requires the collection of all relevant information and data so that a critical analysis of the problem is possible. This analysis leads to the development of a set of available alternative courses of actions that could be used to solve the problem; only realistic solutions should be selected, and the selection should take into account multiple criteria (e.g., effectiveness, benefits, costs) and those constraints that will restrict that number of alternatives (e.g., ease of implementation and technical or legislative constraints). Alternatives should be ranked in terms of how attractive they are to the decision maker when all the criteria are considered simultaneously. Based on this analysis, the best solution is selected, and the decision is converted into an action. This phase of decision-making might be regarded as a problem-solving activity that is terminated when a satisfactory solution is reached. Thereafter, the decision maker has to take follow-up steps for the execution of the decision taken.

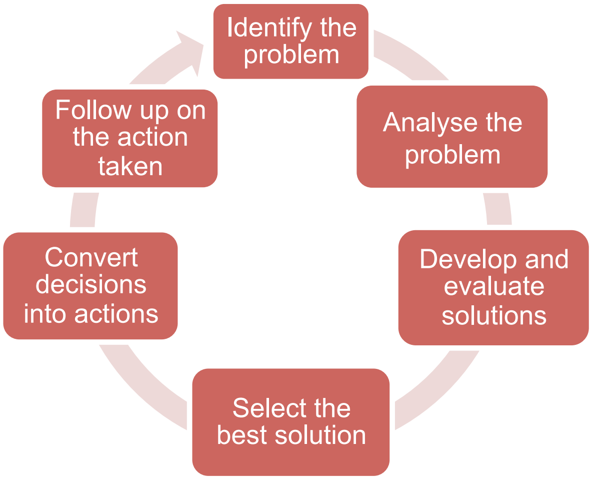

Figure 6. The chain of the decision-making process.

The process described above applies to four main elements of decision-making: What? When? How? and Who? Each of these elements presents further options, resulting in multiple decision-making mechanisms (Figure 7). Decision-making can be a reasoning process, an information-based process, or an intuitive process. Most decisions are made intuitively because it would take too much time to list the advantages and disadvantages of each decision. Especially when decisions must be made quickly and when the stakes are high or when the solutions are uncertain, experts typically rely on intuitive decision-making rather than a structured approach, i.e., they immediately arrive at a course of action without weighing alternatives. Decision-making can be proactive (e.g., schedule a preventative fungicide spray) or forced by an event (e.g., an unexpected disease outbreak). Operational decisions are frequently made in response to unforeseen events and are usually intuitive and made by individuals. Strategic decisions are usually proactive, based on information, and frequently involve more than one person (e.g., the farmer and a pool of experts).

Because the decision-making process in modern agriculture has increased in complexity (McCown, 2002b), farmers must invest time in management, business planning, identification of required skills, and training to ensure that the correct crop management operations are selected. In IPM, time must also be invested in data collection and detailed record keeping. In addition, decision makers must be provided with adequate methods and tools as well as threshold values to help them determine where, when, and what kind of treatments are needed, and they must be aware of the full set of up-to-date information for the specific crop, pest, or disease. This means that they must have access to detailed and factual information. Decision makers must also know where to obtain expert advice, and they must be willing to accept scientific and technical advances that benefit the environment, food quality, and economic performance, and that can be integrated into the crop management as soon as they are determined to be reliable (EISA, 2001).

It is clear that the IPM framework of Figure 2 will work only if the decision makers are adequately supported. The Directive 128/2009 states that Member

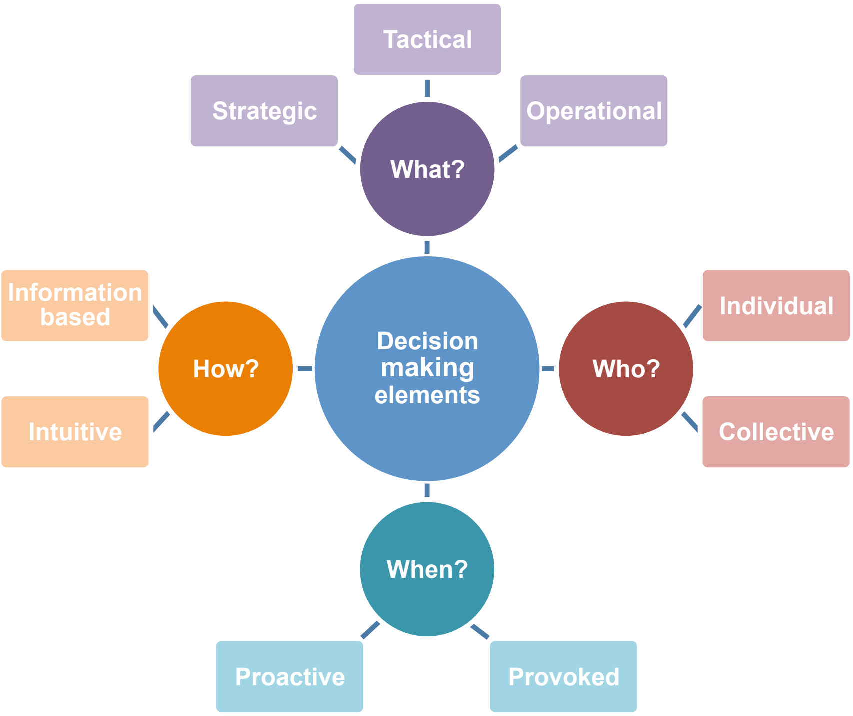

Figure 7. Diagram of the four key decision-making elements: What? When? How? Who? Different decision-making mechanisms emerge based on the combinations of options around each of the four elements (modified from Bowett, 2012).

States shall establish or support the establishment of necessary conditions for the implementation of IPM. In particular, they shall ensure that professional users have at their disposal the information and tools required for pest monitoring and decision-making and that they also have access to IPM advisory services.

This paper aims to review the evolution of methods and tools used for helping farmers in decision-making for crop protection, to provide a framework for classification of these tools and to analyse their weaknesses and strengths for practical application on IPM. Review of currently available tools for specific crops or diseases is not within the aims of this paper.

Tools for decision-making in IPM

Different tools have been developed for the support of decision-making in plant disease control, and these can be grouped into three categories: i) warning services; ii) on-site devices; and iii) decision support systems (DSSs). These work at different spatial and time scales, are provided to users both by public and private agencies (Figure 8), and focus on different communication modes. The simplest form of this communication occurs when the provider uses the decision support tool to communicate with a user who acts only as a receiver. Such a one-way pattern of communication is appropriate for well-bounded and small problems (McCown, 2002a). Many problems, however, require different kinds of communication. Moore (2007) distinguished the following communication modes: i) 'information base' mode, which operates like a library in that the knowledge to be communicated resides in documents rather than in dynamic form (as in a model), and users select which messages they will access; ii) 'constraint management' mode, which supports a two-way communication process in that the provider communicates information about management practices to a user, and the user in turn uses the tool to demonstrate that some externally imposed requirement has been met (this 'external' requirement may be imposed, for instance, by regulations governing environmental conservation and safety); iii) 'consultancy' mode, in which the problem is defined by

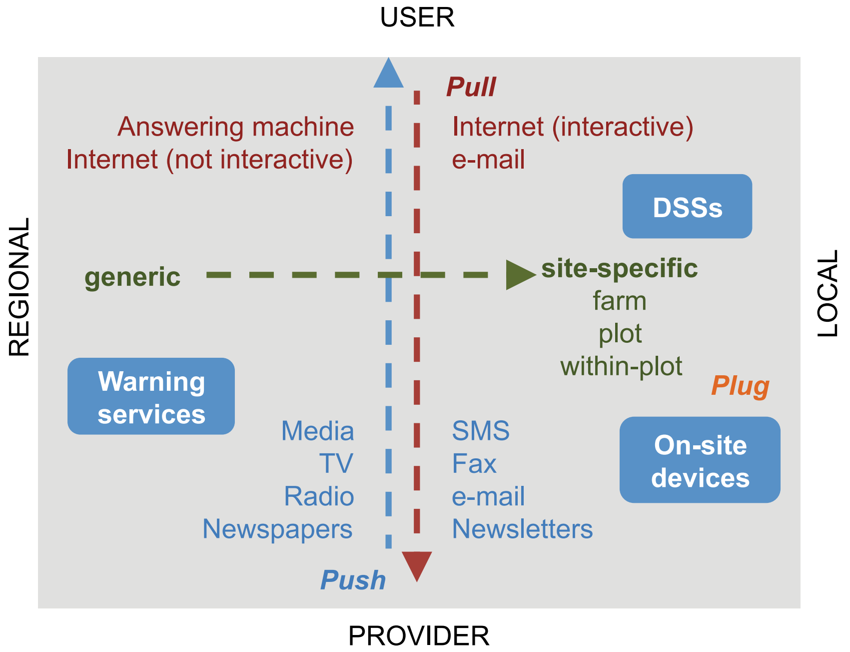

Figure 8. A comparison of spatial scales and delivery mechanisms for decision support tools (warning services, on-site devices, and DSSs) for crop protection (modified from Magarey *et al.*, 2002). DSSs = decision support systems.

the user and comprises context-specific information, which the decision-support tool uses to provide the user with information to consider; and iv) 'learning' mode, in which the tool (more properly described as a 'learning-support tool') conveys understanding about the problem to a user.

Decision-support tools use a variety of delivery networks including word-of-mouth, newsletters, recorded phone messages, facsimile (fax), electronic mail (e-mail), short message services (SMSs), and web sites. Delivery systems have been classified as either 'plug', 'push', or 'pull' (Russo, 2000). Plug systems provide information built into an on-site device. Push and pull systems provide information from a remote source: push systems deliver information to the user, while pull systems require the user to request the information.

Models are key components of any decision-support tool for plant disease control. Models are simplified representations of reality (De Wit, 1993), and plant disease models are simplifications of the relationships between pathogens, crops, and the environment that cause epidemics to develop over time and/or space. There are numerous kinds of models and modelling approaches (Krause and Massie, 1975; Shrum, 1978; Zadoks, 1984; Fry and Fohner, 1985; Campbell and Madden, 1990; Hardwick, 2006; De Wolf and Isard, 2007; Rossi *et al.*, 2010). Prediction of a disease allows growers to respond in timely and efficient ways by adjusting crop management practices (Krause and Massie, 1975; Zadoks, 1979; Rabbinge *et al.*, 1989; Maloy, 1993); a prediction of low disease risk may result in reduced pesticide application with positive economic and environmental effects. Most reviews of plant disease prediction models show that far more models have been developed than have been applied (Krause and Massie, 1975; Butt and Jeger, 1985). A recent study (De Wolf and Isard, 2007) showed that the imbalance between the number of models developed and deployed may be changing, and also indicated that the research effort directed toward evaluation and practical application of disease prediction models is currently much greater than just a few decades ago. Madden *et al.* (2007) developed the concept of risk algorithm as 'any calculation that uses observations of identified risk factors from the host crop, the pathogen population and the environment to make an assessment of the need for crop protection measures'. Plant disease models produce predictions about epidemics or single epidemic components that can be used as risk indicators. Such models also produce predictions about plant disease epidemics that can be used for decision-making concerning plant disease management in production fields at the different spatial scales.

Warning services

Warning services are usually offered to farmers by extension services or other public agencies free of charge or with payment of access fees. In most cases, the agencies deliver general crop protection information and advice: i) for a group of farmers and without consideration of the peculiarities of each farm or of specific environmental and crop conditions; ii) at the regional scale (i.e., for homogeneous areas); and iii) at fixed-time intervals (with daily to weekly updates). In some cases, the warnings are based only on pre-defined IPM guidelines but frequently the warnings are based on model assessment of environment-driven risk (Rossi *et al.*, 2000). Most warning services use one-way communication; in some cases, the 'information base' and 'constrain mangement' modes of dual communication are used. In warning services, information is delivered with both push and pull approaches. The media (local TV, radios, and newspapers) are frequently used in push-type systems; first warning systems developed at the end of the 1980s largely used videotext, as was the case in southern Ontario, Germany, Belgium, Ireland, the Netherlands, and Switzerland (Pitblado, 1988; Carletti and Claustriaux, 1991; Dunne, 1991; Forrer *et al.*, 1991). Specific messages in answering machines and non-interactive web sites are typical pull-type systems. Information delivery has evolved over time with the development of new information and communication technologies (ICTs). For instance, in Norway a bulletin board system was set up in the early 1990s, and this was followed some years later by a voice board system called TELEVIS. The bulletin and the voice board provided the results of the monitoring of diseases and pests in small grain cerals together with the results of NORPRE (a model platform for diseases and pests on barley and wheat), the recorded weather data, and the weather forecast (Magnus *et al.*, 1991, 1993). In 1995, the system in Norway was expanded with new models for cereals, potato, fruit, and vegetables (Magnus, 1995). In 2001, a new web-based warning system (VIPS) was developed, and VIPS provides warnings for several pests in fruit, vegetables, and cereals in Norway (Folkedal and Brevig, 2003). Currently, the most common way for delivering information to farmers is via non-interactive web sites.

Some warning services combine collective and individual warnings; they use ordinary mail, fax, e-mail, or SMS technology for delivering generic information to individual farmers (push approach). The delivery of information to individual growers has changed over time due to new ICTs. For instance, in the 1970s Italian sugarbeet growers received post cards with the date when the first fungicide spray against Cercospora leaf spot was necessary in their particular beet-growing area, while SMS-based advice is currently available (Beta, 2011).

SMS technology is a promising solution for those farmers who are still reluctant to use computers and/or who need the information when they are in the field and are far from a computer with an Internet connection. Most farmers own mobile telephones that can send and receive SMSs. The SMS technology can be used for various types of communication, which include the following: i) information (the message provides relevant information without the expectation of user response or action); ii) notice (the message notifies the user that some information is available at his/her personal web page, and the user decides whether it is convenient to access it); iii) alarm (the message notifies that an event has occurred to which the user must pay attention); and iv) dialog (i.e., a sequence of related SMSs consisting of requests and responses between the user and provider) (Jensen and Thysen, 2003). Interestingly, the SMS technology makes it possible to use both push and pull approaches (Jensen and Thysen, 2003). Push-type messages can be sent regularly and automatically, and users must specify what kind of advice must be sent, how often, and under what circumstances. Pull-type messages are sent only when users requests them by sending SMSs to particular telephone numbers: a specific functionality of the service finds the user and his geographical location in a subscription database, extracts the relevant data, generates the requested SMS message, and returns the message to the user in a few minutes.

In this context, new generation smartphones and tablets can be important tools for disseminating information. Within the Integrated Pest and Crop Management programs of the University of Wisconsin (Madison, WI, USA), the 'ipmToolkit' (version

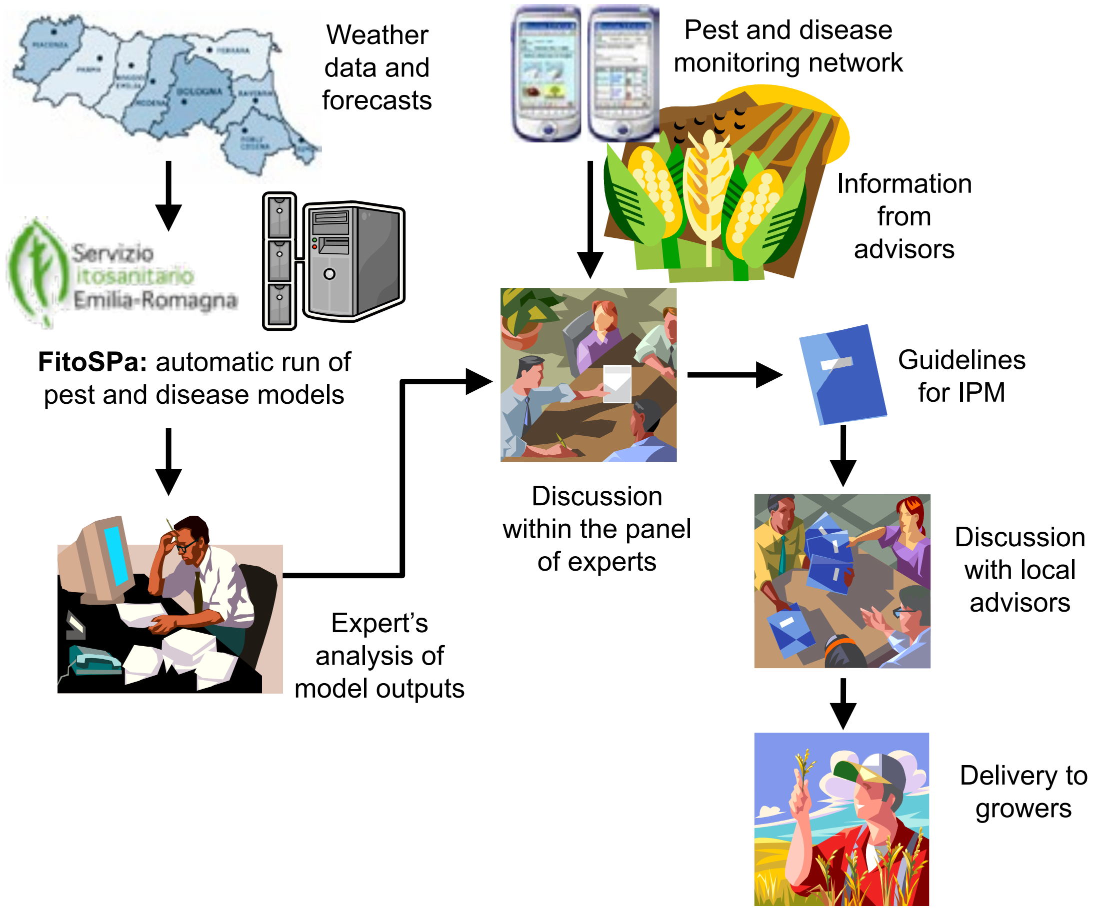

Figure 9. Organization and information flow in the warning service of the Emilia-Romagna (North Italy) provided by the regional plant protection organization (Servizio Fitosanitario). Weather data are used as input for pest and disease models on a daily basis; fields are monitored for pests, diseases, and other aspects of production at weekly intervals. Experts and advisors discuss the information, usually at weekly intervals, and provide guidelines and warnings to growers.

1.01 available at http://itunes.apple.com/us/app/ipm-toolkit/id504685615?mt=8) is released free of charge, downloadable on smartphones and tablets, and allows farmer to read news articles, view videos, download publications, and access pictures which will aid them in adapting IPM practices to their agricultural operations. Another informative tool was developed by the Brazilian consortium for management of soybean rust (Consórcio Antiferrugem, Embrapa): it is a Google-based technology tool for mapping both onset and intensity of soybean rust across the country (Del Ponte *et al.*, 2007) and is made available for free to the growers through an Apple based application for smartphones and tablets (Pavan *et al.*, 2011).

Warning services are currently operating in several European countries, with different organisational schemes. Representative examples for Italy, Germany, and Denmark are described in the following paragraphs, and additional examples are discussed by Nieveen and Bouma (2008).

In Italy, warning services are usually provided by regional governments (Rossi *et al.*, 2000). In the Emilia-Romagna region, for example, the Plant Protection Service manages an advisory service for farmers; the "Forecasting and Advisory Service" follows IPM guidelines and involves collaboration with advisors at the district level and with university scientists (Bugiani *et al.*, 1996) (Figure 9). Information concerning weather conditions and forecasts, crop growth and health, and risk for key pests and diseases of the main crops is analysed by a panel of experts once a week based on weather data provided by the agrometeorological service, scouting data collected on a network of reference crops, and ouput from mathematical models. A specific software was developed for this purpose; it runs several models on a daily basis over a grid of 5 × 5 km that covers the agricultural area of the region. The panel of experts, composed of senior advisors from the districts of the region, produces guidelines that are then used for creating technical bulletins for IPM at the district level; the panel of experts also receives input from local advisors from local government and grower associations (in 1995, 152 advisors were involved in total; Schipani and Malavolta, 1995).

In Germany, the PASO-project began in 1993 and involved 13 Plant Protection Services from 11 Federal States (Kleinhenz *et al.*, 1996). To ensure the continuation of this service, a specific institution was founded in 1997 by administrative agreement among the States and was named the Central Institution for Decision Support Systems in Crop Protection and Crop Production (German acronym ZEPP) (Kleinhenz and Rossberg, 2000). The mission of ZEPP is to develop, collect, and examine existing models for important pests and diseases and to adapt these models for practical use. In recent years, ZEPP has developed over 40 weather-based models; these allow decision makers to estimate disease/pest risks, to estimate the need for and the optimal timing of pesticide treatments, to determine the optimal timing for field monitoring, and to recommend appropriate pesticides (Racca *et al*,. 2011). Model outputs are calculated based on more than 560 weather stations. Every day, and by means of different media (bulletins, letters, faxes, and telephone answering machines), German farmers receive updated predictions covering the entire territory. In 2000, ZEPP began to develop an Internet-based warning system that integrates models, comprehensive up-to-date monitoring in farmer fields, and specific advice from extension officers; this warning system is accessible via the Internet platform www.isip.de (Information System for Integrated Plant Production) (Röhrig and Sander, 2004).

In Denmark, the PlanteInfo web site (www.planteinfo.dk) provides information for farmers and advisors. PlanteInfo was developed and is operated within the Danish agricultural research community in close collaboration with the Danish Agricultural Advisory Centre (DAAC) with funding from Danish agriculture; the weather data are supplied by the Danish Meteorological Institute (Jensen *et al.*, 2000; Thysen, 2007). Information for plant protection is obtained from three sources: i) local, up-to-the-hour weather data and weather forecasts; ii) field observations by crop production advisers; and iii) an interactive decision-support system, named Plant Protection Online, which uses the indicated data and covers weeds, diseases, and pests. Most of the contents of PlanteInfo are delivered as personalized web pages requiring login. DAAC operates a comprehensive system for the weekly monitoring of crop diseases and pests in collaboration with local advisory officers; the data are recorded by personal digital assistant (PDA) and are transferred electronically to a database with indication of the locations of the fields inspected. The information is then available in PlanteInfo as a GIS application with expert recommendations by DAAC formulated according to the current observations. The observed disease levels are then combined with a set of rules for recommending treatments depending on the crop and the variety. These recommendations are presented in the GIS application with green, yellow, and red colours. Weather-based warnings for pests are also presented in maps marked by green, yellow, and red to visualize local risk levels, graphs of temperature data, together with graphs of data and risks from previous years. Plant Protection Online also has tools for seasonal planning; for identifying weeds, diseases, and pests; for problem solving; and for obtaining essential information concerning pesticides and the formulation of pesticide mixtures (Rydahl *et al.*, 2003).

Similar approaches are pursued in non-European countries. For instance, the Pest Information Platform for Extension and Education (PIPE) was created in the USA, which integrates experts, information and communication technologies in order to enhance the use of DSSs, trigger development of new IPM programs, spread information and help growers in their management actions (Isard *et al.*, 2006). The ideal base of this PIPE is the knowldege from research, while scouting activity on sentinel plots and diagnostics by the USDA are used to confirm the outbreak of diseases for giving credibility to the system. All the data are timely made available among various government and private agencies to run models in order to eventually analyse and intepret situations, define management guidelines for growers and disseminate them via the Internet (VanKirk and Isard, 2012). The first case study used to enhance ipmPIPE activities was for soybean rust (Isard *et al*., 2006), then it was also adopted for cucurbit downy mildew (Ojiambo *et al*., 2011), pecan (Calixto *et al*., 2011) and legumes productions (Langham *et al*., 2011).

Another example is offered by *MyPest Page* (http://uspest.org/wea/), a website that brings together US weather data and plant pest and disease models to serve many decision support needs in agriculture. At present over 78 degree-day and 18 hourly weather-driven models are provided. Models serve many IPM, regulatory, and plant biosecurity uses for the whole USA. In this example, all data are provided 'as is' and users assume all risk in their use.

On-site devices

On-site devices provide information at farm or plot levels by means of one-way, plug approaches. These devices usually incorporate models (e.g., one or a few models for specific crops and diseases or pests) and the weather sensors that collect the model input data, and produce output specific for the site where the device is located. They are often marketed by private companies, frequently by those selling weather stations for agriculture. The companies do not usually support farmers in using and interpretating the model outputs. These models are typically taken from the literature and lack specific validation or calibration for the local conditions where the device is operated. Alternatively, the models working within these products are not transparent and have not been published in peer-reviewed scientific journals.

These electronic devices appeared on the market in the 1980s. In Italy, for example, devices such as AGREL, BIOMETRON SWG, MTX WST 4000, and SIAP 3800 predicted grape downy mildew and apple scab infections (Mandrioli *et al*., 1985; Gianetti *et al*., 1986). Another device that is currently available, the Lufft HP 100, is a stand-alone system that continuously measures and records temperature, humidity, precipitation, leaf wetness, and light intensity, and provides integrated disease calculations for orchards and vineyards.

Some of these devices send the weather data to servers managed by the providers, and farmers access both the data and the outputs of disease/pest models through the Internet (e.g., those from Pessl Instruments, http://pessl.metos.at, or Dacom, www.dacom.nl). The iMETOS® weather stations produced by Pessl Instruments are available with sensors and matching software for prediction of some plant diseases. Stations transfer weather data wirelessly to the Internet, where farmers have their own platforms (purchased from the company) for data storage and processing. The platform can be accessed via personal computer, notebook, PDA, or mobile phone. Others devices require the installation of specific software in the farmers' personal computers (e.g., the devices from Davis Instruments, www.davisnet.com).

Alternatively to on-site weather stations weather data can be generated using Geographic Information System (GIS) programs to generate interpolations of weather data accounting for different altitude and location. The company SkyBit Inc. (Bellefonte, PA, USA) is providing an almost full coverage of cultivated area in North America collecting data from hundreds of different weather stations (public or private) (Russo, 2000), using the Geo Positioning System (GPS) software to pinpoint the location of each farm or field, and GIS tools to calculate disease risk for farms located between stations (Gleason *et al*., 2008). Preliminary attempts have also been made to use ground-based radar estimations of rainfall as inputs for disease-warning systems, for instance in Italy, to provide an estimation of leaf wetness duration due to rainfall (Cicogna *et al*., 2005).

Tools for precision agriculture can be considered as types of on-site devices. They require site-specific maps accounting for intra-field variation for disease and crop conditions (Bjerre *et al*., 2006). Maps are drawn by using data from automatic monitoring devices (Bjerre, 1999) or outputs of disease models (Rossi, 2003), which use input data from wireless sensor networks installed in the field (Wang *et al*., 2006). These geo-referenced maps are incorporated in on-board computers on tractors and regulate the distribution of the PPP via the Global Positioning System, which defines the exact position of tractors on maps (Rossi, 2003).

Decision-Support Systems

Decision-support systems (DSSs) are a specific class of computerized information system that support decision-making activities. A properly designed DSS is an interactive software-based system that helps decision makers obtain useful information from raw data, documents, personal knowledge, and/or models in order to identify and solve problems and make decisions. DSSs can be as simple as a tool for processing data or as complex as a computerized expert system. A brief history of DSSs can be found in Power (2007). A review of the type, category, and fields of application of DSSs in agriculture was published by Manos *et al.* (2004).

DSSs collect, organize, and integrate all types of information required for producing crops; DSSs then analyse and interpret the information and finally use the analysis to recommend the most appropriate action or action choices (Agrios, 2005). Expert knowledge, mathematical models, and timely data are key elements of DSSs and are used to assist producers both with daily operational and long-range strategic decisions (Sonka *et al.*, 1997). Computer-based DSSs have the potential to be important tools in the decision-making process for farmers and their advisers (Ritchie, 1995). DSSs can potentially include all the requirements for practical implementation of IPM.

Status and perspectives of DSSs in IPM

The importance of computer-based DSSs has steadily increased since the 1980s, and a large number of DSSs have been developed to assist extension agents, consultants, and growers in crop management. DSSs can provide users with information on plant disease risk by putting scientific knowledge and rational risk management algorithms at farmers' disposal (Gent *et al.*, 2011; Hochman and Carberry, 2011). Such information can be used for scheduling treatments in a way to target them to the actual needs of control.

Soon after the introduction of personal computers and modems to farms, government-funded programs were created in several countries to speed the introduction of this new technology, to enhance the use of personal computers on farms, and also to enhance the development of models and the exchange of information (Meijer and Kamp, 1991). Furthermore, some EU-funded concerted actions (EU.NET.DSS) and EU-cost actions were designed to stimulate the development and introduction of this new information technology as a common initiative (Secher, 1993). EPIPRE (Daamen, 1991) was one of the first computerised advisory systems for supervised integrated control of wheat diseases in Europe.

A review on the DSS currently available for crop protection in Europe was performed by the EC-funded ENDURE - Network of excellence in 2008 (ENDURE, 2010). This review was based on a survey of 70 DSSs, selected on the basis of four eligibility criteria: i) evaluation of economic thresholds and/or recommendation of options for treatment; ii) integration of various sources of information; iii) use of decision algorithms and/or calculation models; and iv) use of computers. The survey classified the selected DSSs into the following groups (the number of records belonging to each group is indicated in brackets): diseases in horticultural and fruit crops (18); diseases in arable crops (37); pests (18); weeds (9) (the sum of the records is higher than 70, because some DSSs consider more than one adversity). The DSSs included in the survey were analysed for the kind of decisions they support, the modelling approaches they are based on, the modality of communication with users, the demonstrated impact, the opportunities for integration with naturally adjacent systems, the implementation of procedures for updating, and the possibility of providing feedback to research.

Similarly, a list of DSSs for managing climate-dependent farm business has been produced for Australia by a panel of experts; such a list is available on the web-site of the service Climate Kelpie (2012). A total of 28 tools was identified, of these only three are focused on plant protection.

DSSs have generally contributed little to practical agriculture and, compared to the number of DSSs that have been developed, and only a few are routinely used (Nguyen *et al.*, 2006; Matthews *et al.* 2008; Gent *et al.*, 2011). Although farmers want enhanced ability to solve, resolve or avoid problems and uncertainty in decision-making, DSSs are amongst the least preferred ways for achieving this goal (Stone and Hochman, 2004). The adoption of DSSs has been quite weak, with a number of users ranging between a few enthusiasts users and up to just 3% of the number of professional farmers in a single country (DCA, 2012). In particular, the direct use of DSSs for crop protection by farmers is low, and the main use is indirect via agricultural advisors (ENDURE, 2008). Similarly, Jones *et al.* (2010) described as 'super users' those office employees who access the systems for several weather stations and then distribute model outputs to people implementing the IPM on tree fruits.

As it was indicated at the beginning of the 2000's (McCown, 2002b), DSSs for crop management faced, and are still facing (Matthews *et al.*, 2008; McCown, 2012), the so called Information System 'problem of implementation', that is the "lack of sustained use in a way that influences practice" (McCown, 2002b).

Thorough analyses of the reasons of non-adoption and failure of DSSs in agriculture have been carried out by several authors, who in turn reflected on the possibility of recovering from the mistakes of the past (Parker *et al.*, 1997; Magarey *et al.*, 2002; McCown , 2002b; Stone and Hochman, 2004; Matthews *et al.*, 2008; McCown *et al.*, 2009; Ascough *et al.*, 2010; Hochman and Carberry, 2011;). Different factors have been identified that influence the adoption and sustained use of DSSs by agricultural users: profitability, user-friendly design, time requirement for DSS usage, credibility, adaptation of the DSS to the farm situations, information update, and knowledge of the users (Kerr, 2004). Under-utilization can be ascribed both to technical limitations and farmers' attitude towards decision-making and perception of DSSs (Matthews *et al.*, 2008; Gent *et al.*, 2011).

Limitations of existing DSSs

Many of the technological problems met during the 1990's, and recognized to be obstacles to the adoption and sustained use of DSSs, have been significantly reduced by the increased availability of personal computers, access to the Internet, and development of web-based programs (Jones *et al.*, 2010). Nevertheless, despite the development and diffusion of ICT that has occurred over the last decades and the fact that the current generation of producers are adopting computers at the same rate of the general public (Ascough *et al.*, 2010), some limitations still exist. Below is provided a list of limitations to the widespread use of DSSs, most of which have been overcome in some new DSSs, but still persists in other realities.

A first limitation is that DSSs do not adequately consider all aspects of production (Parker *et al.*, 1997; Rossing and Leeuwis, 1999; BCPC, 2000; Magarey *et al.*, 2002). Most of the currently available DSSs address only specific problems, whereas agricultural producers must manage a wide range of problems generated by the entire production systems. Some DSSs are too simple or were built to solve problems that do not concern real-world users (Magarey *et al.*, 2002). For example, several DSSs focus on saving an individual spray, but real-world users are often more concerned with maintaining quality standards or meeting regulations. Part of this problem stems from the fact that while researchers often concentrate on a single pathogen, growers must deal with all aspects of farm management, including labour, equipment, finances, cultural practices, and management of an entire complex of several microbial and arthropod pests.

A second limitation is the low quality of the products. This has arisen because it has become very easy to deliver information electronically. As a result, models are sometimes pushed into service before they have been sufficiently refined and validated. Frequently, there is poor communication between the DSS developers and users, so that the refinement phase of the DSS products is lacking. This is particularly true for commercial DSSs (Magarey *et al.*, 2002).

A third limitation is that many agricultural DSSs do not have user-friendly interfaces. Cultivation decisions are complex by nature: they involve many interacting factors and have trade-offs between risk and reward, and/or involve uncertainty (mainly due to the erratic climate) (Clemen, 1991). DSSs vary in complexity, with production guides at the simple end of the spectrum and a full-expert system at the complex end; both simple and complex DSSs have disadvantages (Magarey *et al.*, 2002). Farmers generally require clear and concise information, and usually react unfavourably to the delivery of large amounts of redundant information (i.e., information not directly relevant to the producer decision-making process) (BCPC, 2000; Ascough *et al.*, 2010). Worm *et al.* (2010) showed that the acceptance and appreciation of a DSS increases in accordance to the "look and feel" of the system. Historically, many DSSs have presented their outputs in quantitative terms, which growers find difficult to interpret. Simple symbols can often be used to indicate levels of risk that can be associated with a management consequence (Magarey *et al.*, 2002). Furthermore, DSS output frequently lacks flexibility (Ascough *et al.*, 2010). Many DSS tools use only one method in the information flow, with the result that some users find the information too complex, while others find that the information does not allow them to choose among several management options.

A fourth limitation concerns the time required to operate the DSS. Several DSSs require too much time to use because of delays in data processing or tedious input requirements. For example, the users of the GPFARM, a DSS for strategic planning of whole farms, did not have the time to fill in the system with the numerous information requested as input by the system (Ascough *et al.*, 2010); moreover, the run-time was too long, discouraging producer/consultant adoption. The time demand on users can be the single most important factor in the success or failure of a DSS (Travis and Rajotte, 1996).

A fifth limitation is that the DSS outputs are not properly updated. Crop management decisions cannot be postponed and many DSSs do not meet the time interval growers use to make decisions. For example, grapevine growers normally consider half-day intervals for controlling downy mildew. They will make decisions for the morning, the afternoon, or the next morning. Difficulties in rapidly updating the default DSS databases (e.g., climate data and PPPs) can reduce the usefulness of the system to the growers (Ascough *et al.*, 2010).

The sixth limitation is that many DSSs are not properly maintained. Modern DSS software and electronic distribution networks are expensive to develop and maintain. The construction of a DSS often requires great time and financial investment, which frequently come from specific projects with adequate financing. When maintenance is not adequately supported, there is often little energy or resources left for maintaining the DSS, and updating with new results from research. Maintenance costs should then be provided in the form of fees paid by users. Jones *et al.* (2010) estimated the value of the fee for a DSS which was provided free of charge up to that moment for IPM in tree fruit. The fee was calculate based on the number of current users and the costs for maintaining and updating the system, as well as the costs for providing training. This study did not include growers' benefits from using the DSS in the calculation of fees the growers had to pay to access the DSS.

User's attitude towards decision-making and perception of DSS use benefits

The lack of success of DSSs in agriculture, despite the progressive overcoming of several limitations met during the 1990's, has brought attention to the importance the potential users give to the role these systems play in decision-making processes (Matthews *et al.*, 2008; McCown *et al.*, 2009). It was considered that the DSS providers had "an excessive focus on technological factors rather than recognizing the need to ensure that the tools developed are credible with decision makers and to integrate the software into a particular decision making milieu" (Matthews *et al.*, 2008).

There is, therefore, need to address the 'Decision' and 'Support' aspects (McCown, 2012) rather than the 'System' technology, by taking into greater consideration the decision-making processes adopted by agricultural users and by emphasising the role of support: users are the ones who make decisions, while software can only assist them (Matthews *et al.*, 2008; McCown, 2012).

Resistance towards DSSs often derives from their designed role in decision making: DSSs typified as 'proxy' for a user's decision process (e.g., elaborate expert systems) have been unsuccessful because farmers felt their decision process was by-passed (McCown, 2002b). Rather than making decisions on behalf of the users by prescribing an action as the optimal solution, DSSs should attempt to help crop managers satisfying their needs in working reality which is characterized by high uncertainty and complexity (McCown, 2002b; Hochman and Carberry, 2011). In this way DSSs assume the role of tools which provide information relevant on the focus of decisions and that the users can consider and apply according to their own decision-making processes (McCown, 2002b; Stone and Hochman, 2004); DSSs then complement the decision-making process without excluding the users from it (Stone and Hochman, 2004). For this reason, DSSs serving as tools have generally experienced higher use compared to those designed as proxies.

Another reason of success may derive from the fact that farmers, who are aware that their decision making is impaired by uncertainty (McCown *et al.*, 2009), can positively receive a DSS which allows profitable reduction in uncertainty "by deriving and exploiting 'deep,' abstract information about the system, by introducing a powerful 'logic,' or a combination of both" (McCown, 2002b).

Another factor which influences the adoption rate of a DSS is the establishment of its practical impact and market credentials (Stone and Hochman, 2004). In the context of crop management, the introduction of a DSS represents a 'sustaining innovation', which requires a significant change in practice (or behaviour) (McCown *et al.*, 2009). Compared to the cultivation of a new crop variety, which is defined as a continuous technology, the adoption of a DSS is defined as a discontinuous technology; this adoption requires the implementation of new work procedures at the farm level, such as routine field inspections or the consultation of ICT tools (DCA, 2012). In order to embark on a challenging adoption of a DSS, potential users therefore need to recognize the relevance that this kind of systems can have on their activity as well as the resulting benefits (McCown *et al.*, 2009).

Quantification of economic benefits rising from the use of DSSs has been demonstrated in only a few cases. Caffi *et al.* (2010, 2012) conservatively estimated that the use of DSSs to manage powdery and downy mildews in viticulture reduce PPP applications by 30%; given that conventional application of PPPs for control of these diseases costs about 500 € ha^{-1} per year, a DSS can reduce the cost by 150 € ha^{-1} per year. However, even when DSSs have been demonstrated to provide economic benefits, DSSs have not been widely used (Gelb, 1999; Parker, 1999). Kuhlmann (1999) offered an economic explanation which remains valid: the farming costs are simply more effectively reduced by reducing the production inputs, purchasing cheaper inputs, and simplifying farm operations than through extensive DSS applications. Rather than assessing DSSs according to immediate economic benefits, they should be assessed in terms of overall sustainability, i.e., in terms of economic, environmental, and social sustainability. In this sense, the advantages from using a DSS are manifold. DSSs make it possible to: maintain the natural resource base of the farm for future crop production; better manage resources and reduce certain inputs (e.g., fertilisers and pesticides); improve the quality of the final product; demonstrate to customers and to the general community good environmental performance; meet industry, community, and government expectations about environmental management; and maintain or gain access to certain markets, especially those with high standards for product quality and/or environmental safety. However, quantifying all of these economic advantages that relate to sustainability is not easy.

Involvement of the potential users during the DSS development has been identified as a way of avoiding the implementation problems (Igbaria and Guimaraes, 1994; McCown, 2012; Oliver *et al.*, 2012). User involvement has proved to significantly impact on: perceived DSS benefits, overall user satisfaction, and DSS usage (Igbaria and Guimaraes, 1994). Oliver *et al.* (2012) drew a formalised protocol to promote farmer participation as an integral part of DSS evolution and provided an example for the UK.

An innovative approach to DSS development and implementation

Magarey *et al.* (2002) imagined an ideal, 21st century DSS that overcomes all the previously described technical limitations, and referred to this DSS as the 'super consultant'. The super consultant incorporates total management solutions for growers; moreover, it is designed as a tool to be used by and not for replacing the decision maker. Such a tool helps the user making choices by providing additional information; the user remains responsible for the choice and the implementation of actions (Harsh *et al.*, 1989; Matthews *et al.*, 2008).

The super consultant must be delivered through the World Wide Web (Magarey *et al.*, 2002). A website eliminates the need for software at the user level and provides a mechanism for merging push and pull approaches (Jones *et al.*, 2010). Furthermore, it allows the DSS to be updated easily and continuously, so that new knowledge can be provided to farmers even before it is published in research journals (Reddy and Pachepsky, 1997). The super consultant also has greater automation of interpretation than the current DSSs (Magarey *et al.*, 2002). This requires that decision supports are based both on static-site profiles and site-specific information; the static-site profile information includes factors about the site that do not change substantially during the growing season (such as previous crop, soil characteristics, and cultivar), while site-specific information may change continuously and must be transmitted directly to the web-based DSS as measurements (such as weather data) or scouting reports (such as the current crop status). Additional advantages arising from the use of web-based DSSs are: i) improved two-way interaction with the users; ii) reduction of information production costs; iii) improved checking of system performance; and iv) increased access to multimedia tools (text, graphs, maps, photos, and video). Based on the previous considerations, an innovative DSS aimed at overcoming most of the obstacles that usually limit DSS use in practical crop management should be designed following the conceptual diagram in Figure 10. As indicated, both static-site profiles and site-specific information (data) flow from the environment via instrument sensors or human activities (scouting, chemical analyses) to a database. The information is manipulated, analysed, and interpreted through comparison with available expert knowledge as part of the decision process. The in-

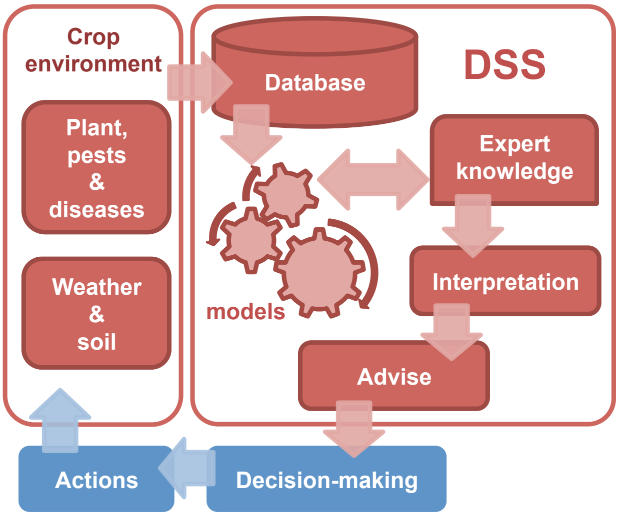

Figure 10. Scheme of an innovative Decision Support System (DSS) for plant disease management. The information flows to and from the environment in an endless loop that begins with sensing and ends with action. Models are the key component of the DSS. The DSS provides information and guidance to the user but the user makes the decisions.

formation is processed to produce a 'decision support' instead of a decision. The decision itself is the responsibility of the user. Rather than replacing the decision maker, the DSS helps the decision maker select among available actions by providing additional information. A decision results in an action to be executed within the crop environment. After the action is implemented, the environment is again monitored to begin a new cycle of information flow. Thus, information flows to and from the environment in an endless loop that begins with sensing and ends with action (Sonka *et al.*, 1997).

This innovative approach is leading to a 'new generation' of DSSs. An example is the DSS for viticulture that is under development by the EU-funded project MoDeM_IVM (Monitoring and Decision Making in Integrated Vineyard Management, Grant Agreement 262059; www.modem-ivm.eu) (Figure 11), which will be delivered as a prototype by the end of 2012. In this DSS, the provider closely interacts with the decision makers for designing the best monitoring system for each particular situation. Af-

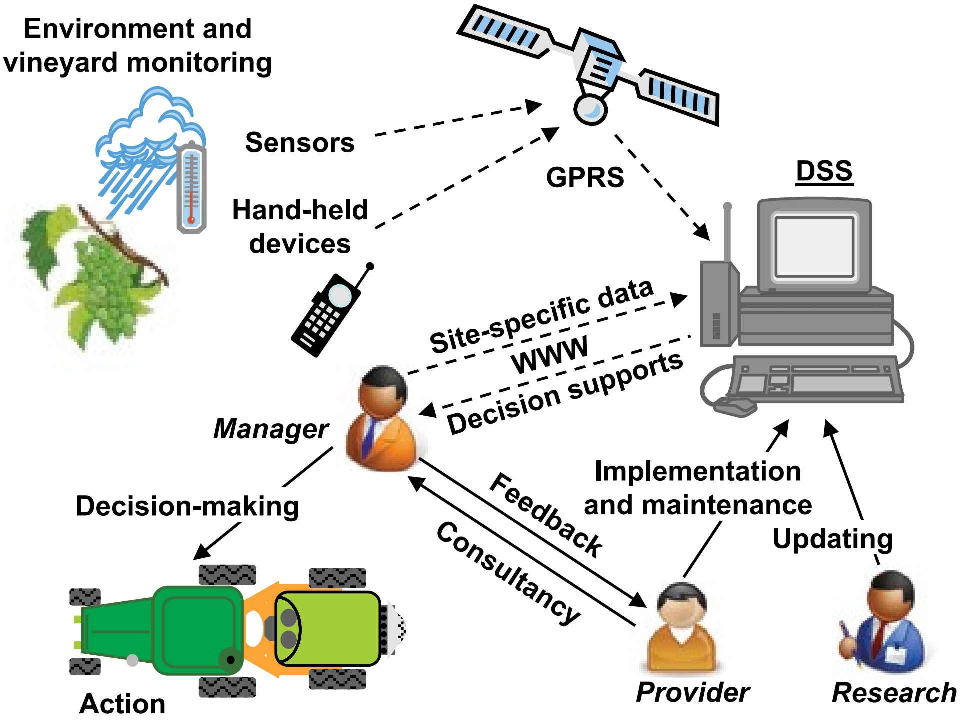

Figure 11. Scheme of activities, tools, data flows, and subjects involved in the development of a Decision Support System (DSS) for integrated management of vineyards, as in the EU project MoDeM_IVM (Monitoring and Decision Making in Integrated Vineyard Management).

terwards, the DSS provider implements the wireless sensors network (WSN) for monitoring the vineyard environment (weather, soil, and plant), provides the grapevine manager with the necessary hand-held devices for scouting the vineyard(s) during the season, and trains her/him in using both devices and the web-based DSS. The grapevine manager uses the DSS for inserting site-specific data for each vineyard. During the season, the WSN monitors the vineyard environment and sends data to the DSS in real time via the Global Positioning Radio System (GPRS). The DSS analyses data and produces the decision supports; when necessary, the DSS asks the grapevine manager to scout the vineyard through its PDA and other hand-held devices, and to send information. The decision supports help the grapevine manager make decisions about management options. The system includes a continuous updating of the DSS and its adaptation to the client needs. This process involves a feedback from grapevine managers and the involvement of researchers who have been involved during the project as well as other researchers with specific expertise.

During the MoDeM_IVM project, potential users were involved and their participation was crucial because they provided insights on their decision processes and on the criteria adopted to decide actions. Establishment of the DSS impact and of its market credentials were also considered to show potential benefits to future users. Seminars and visits to demonstration vineyards were organised; in these vineyards, performances achieved in plots managed according to the vine manager's usual practice were compared to those achieved by considering the supports provided by the DSS.

A similar, web-based, interactive DSS for holistic crop management of high-quality durum wheat was already developed by Horta srl (www.horta-srl.com) and is currently used in Italy (Rossi *et al.*, 2009).

Conclusion

The trend in agriculture is toward more complex, technologically based crop management, with greater regulation and supervision both by government and processors regarding the use of fertilizers, pesticides, and other chemicals. The Thematic Strategy on the Sustainable Use of Pesticides adopted in 2006 by the European Commission has established minimum rules for the use of pesticides in the European Community so as to reduce risks to human health and the environment. The Directive requires the use of IPM in all the EC Member States by 2014, and asks governments to: i) establish or support the setting up of necessary conditions for the implementation of IPM; and ii) establish and apply methods for determining whether farmers apply IPM principles in practical crop management.

Tools for decision-making in IPM, and particularly the 'new generation DSSs' described in this report, can accomplish both requirements. The site-specific data, scouting reports, and decision supports collected by these DSSs serve as acceptable criteria for justifying (to regulatory authorities, but also to wholesalers, food processers, and consumers) the application of chemicals, and can be used by growers as evidence that they are properly and rationally applying PPPs. In using these DSSs, growers not only satisfy these requirements but also benefit from: i) reduced costs for protecting their crops from pests and diseases because of a reduction in the number of treatments; ii) improved use of the natural resources (soil and water); iii) increased crop quality and quantity, thanks to a better management of biotic and abiotic stresses; iv) reduced labour needed for crop management; and v) reduced costs for external consultancy. The innovative nature of new generation DSSs is based on: i) a holistic vision of crop management problems with the focus on all the different individual operation issues (e.g. pests, diseases, fertilisation, irrigation, canopy management); ii) provision of information on the focus of the decision in the form of easy-to-understand decision supports able to reduce uncertainty; iii) easy and fast access through the Internet; and iv) two-way communication between users and the providers, which make it possible to consider context-specific information. These DSSs combine the advantages of simple DSSs (low cost, ease of delivery in multiple ways, and limited time requirements for learning and using) and more sophisticated ones (greater integration of knowledge, greater grower choice of management tools, and greater consideration of associated risks). These DSSs are therefore easy-to-use tools that perform complex tasks efficiently and effectively. In addition, these systems use technology (Internet, SMS, hand-held devices like mobile phones or PDAs) already available and known to most users. The delivery of these DSSs using the Internet also ensures efficient transfer of scientific knowledge into practical application. The use of the Internet: i) increases the accessibility for the user; ii) allows the DSS to be updated easily and continuously, so that new knowledge can be rapidly and efficiently provided to farmers; and iii) allows users to maintain close contact with providers.

Farmer acceptance of ICTs was disappointing in the 1990s, mainly because farmers were unwilling to invest the time required to learn how to use new technologies (Thysen, 2000; McCown, 2002a). This is rapidly changing, however, as the Internet becomes more available, as technology improves, and as farmer understanding of technology increases. The use of the Internet by farmers should not be a bottle-neck for DSS acceptance because access to the Internet is rapidly increasing in agricultural areas. Surveys by the USDA's National Agricultural Statistics Service found that, in 1999, 40% of US farmers owned or leased computers, although only 29% had access to the Internet (NASS, 2006); by 2011, these numbers had increased to 65% and 62%, respectively (NASS, 2011). A similar trend is occurring in Europe (EITO, 2007). In Italy for example, more than 129,000 farms had internet connections in 2007 (Istat, 2012). The guidelines for rural development for 2007–2013 (Council Regulation (EC) No. 1698/2005) encourage the increase in Internet access and the improvement of other communication technologies in rural areas. The efficient use of ICTs, driven by improved access to high-speed (broadband) Internet, is widely recognised as a key factor for increasing productivity and stimulating innovation throughout Europe, including rural areas {COM(2007) 803, 11.12.2007}. Thus, the efficient use of ICTs should promote entrepreneurship and economic progress in rural areas and thereby increase the competitiveness of agriculture and forestry, diversify the rural economy, and improve the quality of life in rural communities. The European Economic Recovery Plan highlighted the importance of broadband communications for modern economies and aimed to ensure that broadband was available to all Europeans by 2010 {COM(2008) 800, 26.11.2008}. A recent Communication from the Commission to the Council and the European Parliament, named "Better access for rural areas to modern ICT" {COM(2009) 103, 3.3.2009}, defines actions for promoting ICT in rural areas.

As noted earlier, another reason for the failure of many farmers to use DSSs is the poor demonstration of economic benefits (McCown *et al.*, 2009) or the recognition by farmers that they could gain more immediate economic benefits by reducing costs (by simplifying farm operations) than by using DDSs (Kuhlmann, 1999). This concern about short-term economic benefits should now be outweighed by the increasing interest in sustainable agriculture and by the requirement that farmers follow new regulations governing environmental conservation and safety (Gent *et al.*, 2011; Jones *et al.*, 2010). Farmers should now recognize that the benefits from DSSs must be viewed in terms of overall sustainability.

Efforts must be devoted by DSS developers in involving the potential users during the phase of DSS design and development to meet the users' real needs, to adapt the system to the decision-making processes adopted by users, demonstrate multiple benefits rising from the DSS use, and make user's confident with the systems.

Acknowledgements

The work leading to this review received funding from the European Union's Seventh Framework Programme managed by REA-Research Executive Agency http://ec.europa.eu/research/rea ([FP7/2007-2013] [FP7/2007-2011]) under grant agreement No. [262059].

Literature cited

Agrios G.N., 2005. *Plant Pathology*. 5th edition, Academic Press, New York, NY, USA, 952 pp.

Ascough II J.C., G.S. Mcmaster, G.H. Dunn and A.A. Andales, 2010. The GPFARM DS for agroecosystem sustainability: the past, future, and lessons learned. In: *Environmental Modeling International Conference Proceedings* (D.A. Swayne, W. Yang, A.A. Voinov, A. Rizzoli, T. Filatova, ed.). International Modeling and Environmental Software Society, Modelling for Environment's Sake, July 5–8, 2010, Ottawa, Canada, 2540–2547.

Baggiolini M., 1990. Production Intégrée en Suisse. I. Aperçu historique de la production agricole intègrèe. *Mitteilungen Schweizerischen Entomologischen Gesellschaft* 63, 493–500.

BCPC, 2000. The role of decision support systems in the farm business of the future, Discussion Forum, 9 December 1999, IACR-Rothamsted, Harpenden, Hertfordshire, The British Crop Protection Council, Farnham, Surrey, UK.

Beta, 2011. Progetto cercospora: un concreto aiuto per avviare i trattamenti al momento giusto. *Beta News* 5, 2.

Bjerre K.D., 1999. Disease maps and site-specific fungicide application in winter wheat. In: *Precision Agriculture '99: Proceedings of the 2nd European Conference on Precision Agriculture* (J.V. Stafford, ed.), 11–15 July, 1999, Odense, Denmark, 495-504.

Bjerre K.D., L.N. Jørgensen and J.E. Olesen, 2006. Site-specific management of crop diseases. In: *Handbook of Precision Agriculture. Principles and Applications* (A. Srinivasan, ed.), The Haworth Press Inc., New York, NY, USA, 207–252.

Boller E.F., J. Avilla, E. Joerg, C. Malavolta, F.G. Wijnands and P. Esbjerg (ed.), 2004. *Guidelines for Integrated Production - Principles and Technical Guidelines*. 3rd edition, *IOBC/WPRS Bulletin* 27 (2), 49 pp.

Bowett R., 2012. Decision-making in business. Available at (last verified September 2012): http://tutor2u.net/business/organisation/decisionmaking.htm

Bugiani R., R. Tiso, A. Butturini, P. Govoni and I. Ponti, 1996. [Forecasting models and warning services in Emilia-Romagna (Italy)]. *EPPO Bulletin* 26 (3–4), 595–603 (in Italian).

Butt D.J. and M.J. Jeger, 1985. The practical implementation of models in crop disease management. In: *Mathematical Modelling of Crop Disease* (C.A. Gilligan, ed.), Academic Press, New York, NY, USA, 207–230.

Caffi T., V. Rossi and R. Bugiani, 2010. Evaluation of a warning system for controlling primary infections of grapevine downy mildew. *Plant Disease* 94, 709–716.

Caffi T., S.E. Legler, V. Rossi and R. Bugiani, 2012. Evaluation of a warning system for early-season control of grapevine powdery mildew. *Plant Disease* 96, 104–110.

Calixto, A., A. Birt, N. Lee, A. Dean, B. Ree, and M.K. Harris, 2011. Pecan ipmPIPE: harnessing the Internet for stakeholders in production agriculture. *Journal of Integrated Pest Management* 2(2), F1–F6.

Campbell C.L. and L.V. Madden, 1990. *Introduction to Plant Disease Epidemiology*. Wiley, New York, NY, USA, 532 pp.

Carletti G. and J.J. Claustriaux, 1991. Plant protection by videotex: Life and death. *Danish Journal of Plant and Soil Science* 85 (S-2161), 41–43.

Cicogna A., S. Dietrich, M. Gani, R. Giovanardi and M. Sandra, 2005. Use of meteorological radar to estimate leaf wetness as data input for application of territorial epidemiological model (downy mildew - Plasmopora viticola). *Physics and Chemistry of the Earth* 30, 201–207.

Clemen R.T., 1991 *Making Hard Decisions. An Introduction to Decision Analysis*. PWS-Kent Publishing Co., Boston, MA, 557 pp.

Climate Kelpie, 2012 (last verified September 2012) www.climatekelpie.com.au/manage-climate/decision-support-tools-for-managing-climate

Conway G.R., 1984. *Pest and Pathogen Control. Strategic, Tactical and Policy models.* Wiley, New York, NY, USA, 488 pp.

Daamen R.A., 1991. Experiences with the cereal pest and disease management system EPIPRE in the Netherlands. *Danish Journal of Plant and Soil Science* 85 (S-2161), 77–87.

DCA – Danish Centre for food and agriculture (last verified august 2012) http://agrsci.au.dk/en/nyheder/artikel/helping-farmers-make-smart-decisions/

De Wit C.T., 1993. Philosophy and terminology. In: *On system analysis and simulation of ecological processes* (P.A. Leffelaar, ed.), Kluwer Academic Publishers, Dordrecht, 3–9.

De Wolf E.D. and S.A. Isard, 2007. Disease cycle approach to plant disease prediction. *Annual Review of Phytopathology* 45, 203-220.

Del Ponte E.M., G. Tibolla, W. Pavan, C.V. Godoy, S.M.S. Campanini, C.G. Rufino, C.D.S. Seixas and R.M. Soares, 2007. Nova plataforma para o mapeamento da dispersão da ferrugem asiática no Brasil. In: *Simpósio Brasileiro de Ferrugem Asiática*, 2007, Londrina: Embrapa Soja (Documentos 281), 261, 15–20.

Dunne B., 1991. Ireland – status of computer-based advisory systems. *Danish Journal of Plant and Soil Science* 85 (S-2161), 37–40.

EISA, 2001. *A Common Codex for Integrated Farming*. Available at (last verified September 2012): http://ec.europa.eu/environment/ppps/pdf/ilubrochure.pdf

EITO, 2007. *European Information Technology Observatory 2007*, Frankfurt, Germany, 269 pp.

El Titi A., E.F. Boller and J.P. Gendrier (eds.), 1993. Integrated Production – Principles and Technical Guidelines. *IOBC/WPRS Bulletin* 16 (1), 96 pp.

ENDURE, 2008. *Review of New Technologies Critical to Effective Implementation of DSS and FMS*. Deliverable DI2.4, 17 pp.

ENDURE, 2010. *Review of New Technologies Critical to Effective Implementation of Decision Support Systems and Farm Management Systems (DSS's) and Farm Management Systems (FMS's)*. Scientific report, 128 pp. Available at (last verified August 2012): www.endure-network.eu/content/download/4803/39494/file/Review%20of%20new%20technologies%20critical%20to%20effective%20implementation%20of%20decision%20support%20systems%20and%20farm%20management%20systems.pdf

Eom S. and E. Kim, 2006. A survey of decision support system applications (1995–2001). *The Journal of the Operational Research Society* 57, 1264–1278.

European Commission, 2009a. *Development of Guidance for Establishing Integrated Pest Management (IPM) Principles*. Final Report 07.0307/2008/504015/ETU/B3, BiPRO (Beratungsgesellschaft für integrierte Problemlösungen), 111 pp.

European Commission, 2009b. *Draft Guidance Document for establishing IPM principles*. Supplement to the Final Report 07.0307/2008/504015/ETU/B3, BiPRO (Beratungsgesellschaft für integrierte Problemlösungen), 49 pp.

Folkedal A. and C. Brevig, 2003. VIPS – a web-based decision support system for farmers, agricultural extension services and agricultural scientist. *EPPO Bulletin* 33, 451–454.

Forrer H.R., H.U. Gujer and P.M. Fried, 1991. Experiences with and prospects of decision support systems in cereals and potatoes in Switzerland. *Danish Journal of Plant and Soil Science* 85 (S-2161), 89–100.

Fry W.E. and G.R. Fohner, 1985. Construction of prediction models I: forecasting disease development. In: *Advances in Plant Pathology* (C.A. Gilligan, ed.), Academic Press, New York, NY, USA, vol. 3, 161–178.

Gelb E.M., 1999. Adoption of IT by farmers - does reality reflect the potential benefit? In: *Role and Potential of IT, Intranet and Internet for Advisory Services* (U. Rickert, R. Helbig and G. Scheifer, eds.). European Symposium as part of EFITA 99, Second European Conference of the European Federation for Information Technology in Agriculture, Food and the Environment, 27–30 September, 1999, Bonn, Germany, 13-23.

Geng S., C.E. Hess and J. Auburn, 1990. Sustainable agricultural systems: concepts and definition. *Journal of Agronomy and Crop Science* 165 (2), 73–85.

Gent D.H., E. De Wolf and S.J. Pethybridge, 2011. Perceptions of risk, risk aversion, and barriers to adoption of decision support systems and integrated pest management: an introduction. *Phytopathology* 101, 640–643.

Gianetti G., G. Mancini and I. Scapin, 1986. Esperienze di lotta guidata contro la peronospora della vite con l'impiego delle centraline microclimatiche della serie Agrel. *La Difesa delle Piante* 4, 315–334.

Gleason M.L., K.B. Duttweiler, J.C. Batzer, S.E. Taylor, P. C Sentelhas, J.E.B.A. Monteiro and T.J. Gillespie, 2008. Obtaining weather data for input to crop disease-warning systems: leaf wetness duration as a case study. *Scientia Agricola* 65, 76–87.

Hardwick N.V., 2006. Disease forecasting. In: *The Epidemiology of Plant Diseases* (B.M. Cooke, D.G. Jones, B. Kaye, ed.), 2nd edition, Springer, Dordrecht, The Netherlands., 239–264.

Harsh S.B., Loyd J.W. and L.R. Borton, 1989. Models as an aid to decision making. *Acta Horticulturae* 248, 27–48.

Hochman Z. and P.S. Carberry, 2011. Emerging consensus on desirable characteristics of tools to support farmers' management of climate risk in Australia. *Agricultural Systems* 104 (6), 441–450.

Igbaria M. and T. Guimaraes, 1994. Empirically testing the outcomes of user involvement in DSS development. *Omega* 22 (2), 157–172.

IOBC/WPRS, 1977. An approach towards integrated agricultural production through integrated plant protection. *IOBC/WPRS Bulletin* 1977/4, 163 pp.

Isard S.A., J.M. Russo and E.D. DeWolf, 2006. The establishment of a national pest information platform for extension and education. *Plant Health Progress*, doi:10.1094/PHP-2006–0915-01-RV.

Istat (last verified September 2012) http://agri.istat.it/sag_is_pdwout/jsp/dawinci.jsp?q=plSPA0000010000011000&an=2007&ig=1&ct=735&id=46A|69A|68A

Jensen A.L. and I. Thysen, 2003. Agricultural information and decision support by SMS. *Proceedings of the EFITA 2003 Conference*, 5–9 July, 2003, Debrecen, Hungary, 286–292.

Jensen A.L., P.S. Boll, I. Thysen and B.K. Pathak, 2000. Pl@nteInfo – A web-based system for personalised decision support in crop management. *Computers and Electronics in Agriculture* 25, 271–293.

Jones V.P., J.F. Brunner, G.G. Grove, B. Petit, G.V. Tangren and W.E. Jones, 2010. A web-based decision support system to enhance IPM programs in Washington tree fruit. *Pest Management Science* 66, 587–595.

Jordan V.W.L. and J.A. Hutcheon, 1996. Multifunctional crop rotation: the contributions and interactions for integrated crop protection and nutrient management in sustainable cropping systems. *Aspects of Applied Biology* 47, 301–308.

Kerr D., 2004. Factors influencing the Development and Adoption of Knowledge Based Decision Support Systems for Small, Owner-Operated Rural Business. *Artificial Intelligence Review* 22 (2), 127 – 147.

Kleinhenz B. and D. Rossberg, 2000. Structure and development of decision-support systems and their use by the State Plant Protection Services in Germany. *EPPO Bulletin* 30, 93–98.

Kleinhenz B., E. Jörg, V. Gutsche, E. Kluge and D. Rossberg, 1996. Paso – computer-aided models for decision making in plant protection. *EPPO Bulletin* 26, 461–468.

Krause R.A. and L.B. Massie, 1975. Predictive systems: modern approaches to disease control. *Annual Review of Phytopathology* 13, 31–47.

Kuhlmann F., 1999. Farm-level-information-systems: developments and perspectives. In: *Perspectives of Modern Information and Communication Systems in Agriculture, Food Production and Environmental Control* (G. Scheifer, R. Helbig, U. Rickert, ed). Second European Conference of the European Federation for Information Technology in Agriculture, Food and the Environment, 27–30 September, 1999, Bonn, Germany, 7–17.

Langham M.A.C., H.F. Schwartz, S.A. Tolin, J. Golod, J. LaForest and K.F. Cardwell, 2011. Legume ipmPIPE: A new option for generating, summarizing and disseminating real-time pest data to stakeholders. *Journal of Integrated Pest Management* 2 (2): E1–E5.

Madden L.V., G. Hughes and F. van den Bosch, 2007. *The study of Plant Disease Epidemics*. APS Press, St. Paul, MN, USA, 432 pp.

Magarey R.D., J.W. Travis, J.M. Russo, R.C. Seem and P.A. Magarey, 2002. Decision Support Systems: Quenching the Thirst. *Plant Disease* 86 (1), 4–14.

Magnus H.A., 1995. Integrated systems for decision support in plant protection in Norway. *European Journal of Plant Pathology* (Abstracts of the XIII International Plant Protection Congress, 2–7 July, 1995, The Hague, the Netherlands), 943.

Magnus H.A., K. Munthe, E. Sundheim and Å. Ligaarden, 1991. PC-Technology in plant protection warning systems in Norway. *Danish Journal of Plant and Soil Science* 85(S-2161), 1–6.

Magnus H.A., Å. Ligaarden and K. Munthe, 1993. An integrated PC environment for the dissemination of plant protection warnings in Norway, together with weather reports and forecasts. *EPPO Bulletin* 23, 669–671.

Malavolta C. and E.F. Boller (ed.), 1999. Guidelines for Integrated Production of Grapes - IOBC Technical Guideline III. *IOBC/WPRS Bulletin* 22 (8), 2nd edition, 75 pp.

Maloy O.C., 1993. *Plant Disease Control: Principles and Practice*. Wiley, New York, NY, USA, 346 pp.

Mandrioli P., A. Brunelli and G. Veronesi, 1985. Electronic devices for disease forecasting in Italy. *Informatore Fitopatologico* 35 (10), 11–17 (in Italian).

Manos B., A. Ciani, Th. Bournaris, I. Vassiliadou and J. Papathanasiou, 2004. A taxonomic survey of decision support systems in agriculture. *Agricultural Economics Review* 5 (2), 80–94.

March J.G., 1994. *Primer on Decision Making: How Decisions Happen*. The Free Press, New York, NY, USA, 289.

Matthews K.B., G. Schwarz, K. Buchan, M. Rivington and D. Miller, 2008. Wither agricultural DSS? *Computers and Electronics in Agriculture* 61 (2), 149–159.

McCown R.L., 2002a. Probing the enigma of the decision support system for farmers: learning from experience and from theory. *Agricultural Systems* 74, 1–10.

McCown R.L., 2002b. Changing systems for supporting farmers' decisions: problems, paradigms, and prospects. *Agricultural Systems* 74, 179–220.

McCown R.L., 2012. A cognitive systems framework to inform delivery of analytic support for farmers' intuitive management under seasonal climatic variability. *Agricultural Systems* 105 (1), 7–20.

McCown R.L., P.S. Carberry, Z. Hochman, N.P. Dalgliesh and M.A. Foale, 2009. Re-inventing model-based decision support with Australian dryland farmers. 1. Changing intervention concepts during 17 years of action research. *Crop and Pasture Science* 60, 1017–1030.

Meijer B.J.M. and J.A.L.M. Kamp, 1991. Development and introduction of crop management systems. *Danish Journal of Plant and Soil Science* 85 (S-2161), 207–216.

Moore A.D., 2007. Decision support tools: keys to success. In: *Making Science Work on the Farm: a Workshop on Decision Support Systems or Irish Agriculture* (N.M. Holden, T. Hochstrasser, R.P.O. Schulte, S. Walsh, ed.), AGMET, Johnstown Castle, Ireland, 1–10.

NASS, 2006. *Farm computer usage and ownership in 2005*. Available at (last verified September 2012): www.nass.usda.gov/nh/2006FarmComputerUse.pdf

NASS, 2011. *Farm Computer usage and ownership. August 2011*. Available at (last verified September 2012): http://usda.mannlib.cornell.edu/usda/current/FarmComp/FarmComp-08-12-2011.pdf

Nguyen N., M. Wegenr and I. Russell, 2006. Decision support systems in Australian agriculture: state of the art and future development. *AFBM Journal* 4 (1– 2), 15–21.

Nieveen J. and E. Bouma, 2008. *Computer Aids For Plant Protection, Historical Perspective And Future Developments*. Available at (last verified September 2012): www.agrometeorology.org/files-folder/repository/INSAMNieveenComputeraidsforplantprotection.pdf

Norton G.A., 1976. Analysis of decision making in crop protection. *Agro-Ecosystems* 3, 27–44.

Ojiambo P.S., G.J. Holmes, W. Britton, T. Keever, M.L. Adams, M. Babadoost, S.C. Bost, R. Boyles, M. Brooks, J. Damicone, M.A. Draper, D.S. Egel, K.L. Everts, D.M. Ferrin, A.J. Gevens, B.K. Gugino, M.K. Hausbeck, D.M. Ingram, T. Isakeit, A.P. Keinath, S.T. Koike, D. Langston, M.T. McGrath, S.A. Miller, R.P. Mulrooney, S. Rideout, E. Roddy, K.W. Seebold, E.J. Sikora, A. Thornton, R.L. Wick, C.A. Wyenandt, and S. Zhang, 2011. Cucurbit Downy Mildew ipmPIPE: A Next Generation Web-based Interactive Tool for Disease Management and Extension Outreach. *Plant Health Progress*, 11 April 2011, doi:10.1094/PHP-2011-0411-01-RV

Oliver D.M., R.D. Fish, M. Winter, C.J. Hodgson, A.L. Heathwaite and D.R. Chadwick, 2012. Valuing local knowledge as a source of expert data: Farmer engagement and the design of decision support systems. *Environmental Modelling & Software* 36, 76–85.

Parker C., 1999. Decision support systems: lessons from past failures. *Farm Management* 10, 273–289.

Parker C.G., S. Campion and H. Kure, 1997. Improving the uptake of decision support systems in agriculture. In: *Proceedings of the First European Conference for Information Technology in Agriculture* (I. Thysen, A.R. Kristensen, ed.), 15–18 June, 1997, Copenhagen, Denmark, 129–134.

Pavan W., J.M.C. Fernandes, J.H. Debastiani, J. Dalbosco and C.R. Cervi, 2011. Mobile/Wireless Applications in Plant Disease Management. *Tropical Plant Pathology* 36-S, 19–22.

Pitblado R.E., 1988. Development of a weather-timed fungicide program for field tomatoes. *Canadian Journal of Plant Pathology* 10, 371.

Power D.J., 2007. A Brief History of Decision Support Systems. *DSSResources.COM*, Available at (last verified September 2012): http://dssresources.com/history/dsshistory.html

Rabbinge R., J.C. Zadoks and L. Bastiaans, 1989. Population models. In: *Simulation and System Management in Crop Protection* (R. Rabbinge, S.A. Ward, H.H. Van Laar, ed), Pudoc, Wageningen, The Netherlands, 420 pp.

Rabbinge R., W.A.H. Rossing and W. Van Der Werf, 1993. Systems approaches in epidemiology and plant disease management. *Netherlands Journal of Plant Pathology* 99 (Supplement 3), 161–171.

Racca P., B. Kleinhenz, T. Zeuner, B. Keil, B. Tschöpe and J. Jung, 2011. Decision Support Systems in Agriculture: Administration of Meteorological Data, Use of Geographic Information Systems(GIS) and Validation Methods in Crop Protection Warning Service. In: *Efficient Decision Support Systems - Practice and Challenges From Current to Future* (J. Chiang, ed.), InTech, Rijeka, Croatia, 331–354.

Reddy V.R. and Y.A. Pachepsky, 1997. Input Optimization and Crop Management Using Decision Support System GLYCIM/GUICS. In: *Proceedings of the International Congress on Modeling and Simulation* (A.D. McDonald, M. McAleer, ed.), 8–11 December, 1997, Hobart, Tasmania, vol. 3, 1143–1147.

Ritchie J.T., 1995. International Consortium for Agriculture Systems Application (ICASA): Establishment and Purpose. *Agricultural Systems* 49, 329–335.

Röhrig M. and R. Sander, 2004. ISIP - online plant protection information in Germany. In: *Online Agrometeorological Applications with Decision Support on the Farm Level. Cost Action 718: Meteorological Applications for Agriculture* (I. Thysen, A. Hočevar, ed.), *Dina Research Report* 109, Dina Publication, Tjele, Denmark, 41–47.

Rossi V., 2003. Ruolo dei modelli epifitologici nella difesa delle piante dalle malattie. In: *Atti dell'Accademia dei Georgofili, Giornata di studio "Proprietà Ottiche e Stato Sanitario delle Piante: Potenziali Applicazioni nella Difesa delle Malattie"*, 31st October, 2003, Firenze, Italy, VII serie, vol. 50, 275–298.

Rossi V., I. Ponti and P. Cravedi, 2000. The status of warning services for plant pests in Italy. *EPPO Bulletin* 30 (1), 19–29.

Rossi V., P.L. Meriggi, T. Caffi, S. Giosuè and T. Bettati, 2009. A web-based decision support system for managing wheat crops. In: *Advances in Decision Support Systems* (G. Devlin, ed.), InTech, Vukovar, Croatia, 1–26.

Rossi V., S. Giosuè and T. Caffi, 2010. Modelling Plant diseases for decision making in crop protection. In: *Precision Crop Protection - The Challenge and Use of Heterogeneity* (Oerke E.C., R.Gerhards, G. Menz, R.A.Sikora, ed.), Springer Science, Dordrecht, The Netherlands, 241–258.

Rossing W.H.A. and C. Leeuwis, 1999. Quality of modelling for Integrated Crop Management: Introduction to the workshop. In: *Proceedings of the 5th International Symposium on Computer Modelling in Fruit Research and Orchard Management*, 28–31 July, 1998, Wageningen, The Netherlands, *IOBC/WPRS Bulletin* 22 (6), 28–31 / *Acta Horticulturae* 499, 147–150.

Russo J.M., 2000. Weather forecasting for IPM. In: *Emerging Technologies for Integrated Pest Management: Concepts, Research, and Implementation* (G.G. Kennedy, T.B. Sutton, ed.), American Phytopathological Society, St. Paul, MN, USA, 453–473.

Rydahl P., L. Hagelskjær, L. Pedersen and O.Q. Bøjer, 2003. User interfaces and system architecture of a web-based decision support system for integrated pest management in cereals. *EPPO Bulletin* 33 (3), 473–481.

Schipani T. and C. Malavolta, 1995. [Extension services in Emilia-Romagna]. *Agricoltura* 23 (6), 13–16 (in Italian).

Schmid A. (ed.), 1996. Guidelines for Integrated Production in Viticulture. *IOBC/WPRS Bulletin* 19 (10), 36 pp.

Secher B.J.M., 1993. European Network for development of operational and tactical decision support systems for crop protection in agricultural crops. In: *Proceedings of the Workshop on Computer-based DSS on Crop Protection*, 23–26 November, 1993, Parma, Italy, *SP-report* 7, Danish Institute of Plant and Soil Science, 3–4.

Shrum R.D., 1978. Forecasting of epidemics. In: *Plant Disease: an Advanced Treatise* (J. G. Horsfall, E. B. Cowling, ed.), Academic Press, New York, NY, USA, 223–238.

Sonka S.T., M.E. Bauer and E.T. Cherry, 1997. *Precision Agriculture in the 21st Century: Geospatial and Information Technologies in Crop Management*. National Academy Press, Washington, D.C., USA, 168 pp.

Stone P. and Z. Hochman, 2004. If interactive decision support systems are the answer, have we been asking the right questions? In: *New Directions for a Diverse Planet*. Proceedings of the 4th International Crop Science Congress, 26 September – 1 October 2004, Brisbane, Australia.

Thysen I., 2000. Agriculture in the Information Society. *Journal of Agricultural engineering Research* 76, 297–303.

Thysen I., 2007. PlanteInfo – Ten years of online information and decision support for crop production in Denmark. In: *Making Science Work on the Farm: A Workshop on Decision Support Systems for Irish Agriculture* (N.M. Holden, T. Hochstrasser, R.P.O. Schulte, S. Walsh, ed.), Joint Working Group in Applied Agricultural Meteorology (AGMET), Dublin, Ireland, 11–23.

Travis J.W. and E.G. Rajotte, 1996. Implementing IPM through new technology and the non-agricultural community. *Journal of Agricultural Entomology* 12, 219–227.

VanKirk J., and Isard S., 2012. The ipmPIPE: Overview, Lessons, Opportunities, and Challenges. *Journal of Integrated Pest Management* 3(2), 1–7.

Wang N., N. Zhang and M. Wang, 2006. Wireless sensors in agriculture and food industry - Recent development and future perspective. *Computers and Electronics in Agriculture* 50, 1–14.

Worm G.I.M., A.W.C. van der Helm, T. Lapikas, K.M. van Schagen and L.C. Rietveld, 2010. Integration of models, data management interfaces and training support in a drinking water treatment plant simulator. *Environmental Modelling and Software* 25, 677–683.

Zadoks J.C., 1979. Simulation of epidemics: problems and applications. *EPPO Bulletin* 9, 227–234.

Zadoks J.C., 1984. A quarter century of disease warning, 1958–1983. *Plant Disease* 68, 352–355.

Accepted for publication: November 8, 2012