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REVIEW

Sharing decision-making tools for pest management may foster implementation of Integrated Pest Management

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Abstract

Agriculture needs to reduce its current dependence toward pesticides while reducing crop losses caused by pests and ensuring food security; Integrated Pest Management (IPM) is considered the most appropriate approach to achieve the goal. More specifically, growers should use tools that enable informed decisions on whether and when crop protection is needed, and which methods should be used. These tools include risk algorithms, decision rules, intervention thresholds, and decision support systems (DSSs), collectively named decision tools (DTs). A large number of DTs have been developed and made available to advisors and farmers, mainly through Internet-based systems. The adoption rate of these systems, however, has been low because of technical limitations and farmer perceptions. Fragmentation of the DTs offered, poor local implementation, and restriction to particular users are among the causes for low adoption. If properly mobilised, the use and effects of DTs could substantially be increased. Sharing of IPM DTs has a strong potential for providing wider access to the existing knowledge, for fostering IPM implementation, and for supporting plant health policies. In this article, we outline an overall approach to develop a web-based platform, in which DTs are shared and made widely available. Such a platform can include a range of ready-to-use DTs, i.e. DTs which are currently available, that have been field-validated, and which are already being used in some agricultural contexts. The platform also provides open, full documentation of DTs, makes DTs available for validation and adaptation in different agricultural contexts, and makes DTs easily available for multiple kinds of end-users involved in IPM (farmers, IPM experts, public and private information and service providers, and policy makers). We also consider how DT sharing can reduce both the technological and behavioural limitations of existing plant health management systems.

Keywords Crop protection · Pest models · Web-based platform · Digital farming

1 Introduction

Agricultural production is constantly exposed to reductions caused by pests (i.e. any species, strain, or biotype of plant, animal, or pathogen injurious to plants or plant products; ISPM, 2007), which are causing massive losses worldwide (Savary et al., 2019). While a number of approaches exist to manage crop pests, technological progress of chemistry in the twentieth century has led to the development of a large array of synthetic compounds for use as pesticides. Pesticides can be mass-produced at comparatively low cost, are easy to store and transport, can easily and rapidly be used under field conditions, and often translate in both rapid and visible control effects. These are major advantages compared to other means of disease management, such as cropping and cultural practices (Palti, 1981). As a result, agriculture often relies heavily on pesticides, and huge amounts of pesticides are used yearly globally, especially in the Global North, to protect crops from pests, to safeguard agricultural productivity from pest injuries, and to meet public and markets demand for food quality and quantity (Oerke & Dehne, 2004; Savary & Willocquet, 2020; Strange & Scott, 2005). This reliance on pesticides negatively affects human health (Barzman et al., 2015; Loevinsohn, 1987) and the environment (Conway & Pretty, 1991). These collateral effects have led to negative externalities of pesticide-based plant protection, leading to the concept of IPM (Integrated Pest Management; Stern et al., 1957). IPM is the basis of a body of studies summarised in several reviews (Bentley et al., 1995; Jacobsen, 1997; Jeger, 2000; Kogan, 1998; Parsa et al., 2014; Peshin et al., 2009; Thomas, 1999).

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Cost-effective and sustainable IPM practices need to be developed and promoted. According to the FAO, the current definition of IPM "is the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations. It combines biological, chemical, physical and crop specific (cultural) management strategies and practices to grow healthy crops and minimize the use of pesticides, reducing or minimizing risks posed by pesticides to human health and the environment for sustainable pest management" (Table S1).

IPM projects and initiatives started by the 1970s, with major efforts initially in the Global South, at the Centres of the Consultative Group for International Research such as the International Rice Research Institute (Teng, 1985, 1994). Many such projects are now in force worldwide (Radcliffe et al., 2008). In Europe, Directive 128/2009/EC (or SUD, for "Sustainable-Use Directive") defines rules for the sustainable use of pesticides, including the requirement that each European country will establish and support the deployment of IPM. Even though IPM is a cornerstone of SUD, European countries have not yet ensured its implementation (EC, 2017). Between 2011 and 2021, the total volume of pesticide active substances sold in EU countries only decreased by 4.9% (EUROSTAT, 2023). One possible reason for the slow IPM adoption in Europe is that, while the implementation of the general principles of IPM has been mandatory since 2014, the adoption of crop-specific guidelines remains voluntary. In addition, implementation of IPM is considered difficult by farmers because it involves complex decision-making process (Jeger, 2000; McRoberts et al., 2003).

As shown by Europe's SUD and the worldwide literature on IPM, decision-making is an essential component of IPM. In particular, SUD establishes that professional users should have access to information and tools for pest monitoring and decision-making: harmful organisms should be monitored by suitable methods and tools, including field observations; recommendations from advisors should be followed; and warning, forecasting, and early diagnosis systems should be available and used. Based on pest monitoring, professional users decide whether and when to apply plant protection measures. Sound threshold values for pest injury levels (Zadoks, 1985) are also essential components in decision-making.

This review capitalises on the SHARE4IPM (short title for "A multi-user, dynamic, open-source web platform for sharing reliable pest models and supporting decision-making in IPM across Europe"), a proposal submitted to the European Commission and prepared by a consortium of 21 partners from 10 Countries of the European Union and the UK. The present review then emphasises on IPM in Europe and illustrates a project framework as an example of mobilisation of the latest available technologies for sound IPM management decisions. The concepts developed here however have a global scope; even though advanced technologies may not be available in other world regions, we believe that the principles on which this framework is designed are of universal relevance.

2 Decision tools for IPM

Stakeholders are increasingly interested in having access to decision supporting tools for pest control that have been validated and that can be adapted to local conditions in order to implement IPM. Many models (but much fewer decision support systems) have been developed and are being used in specific areas for forecasting the dynamics and management of crop pests and to support decision-making in crop protection. These tools, along with risk algorithms, decision rules, and intervention thresholds, are hereafter referred to as decision tools (DTs). Rossi et al. (2019) recently reviewed the state-of-the-art of DTs for IPM.

DTs usually deal only with limited aspects of crop production and have been mainly developed by national or local research projects. In some cases, tools developed in specific areas have been validated, adapted to local conditions, and used in other areas. A systematic map to identify and catalogue the literature pertaining to disease modelling for agricultural crops worldwide was recently developed (Fedele et al., 2022), showing that most models have been developed in North America and Europe, and mostly for wheat, potatoes, grapes, and apples. This map highlights that the number of studies published was more closely related to the economic value of a crop than to its cultivated area. The map also documented an under-representation of disease models for maize and rice, despite the economic value and the losses caused by pests on these crops.

IPM DTs are, in most cases, currently used locally in IPM programs and are interfaced with warning systems, on-site physical devices (e.g. weather stations), and Decision Support Systems (DSSs) (Rossi et al., 2018). The importance of computer-based DTs has steadily increased since the 1980s, and a large number of tools have been developed to assist extension personnel, consultants, and growers. DTs can provide users with information on crop pest risk, by making scientific knowledge and rational risk management algorithms readily available to farmers (Gent et al., 2011; Hochman & Carberry, 2011). Such information can be used for scheduling pesticide treatments so that they match what is needed for pest control. Soon after the introduction of personal computers and modems to farms, government-funded programs were created to promote the adoption of information technologies (Meijer & Kamp, 1991). EU-funded projects were designed to promote the development and introduction of information technology in crop pest management (Secher, 1993). For instance, Been et al. (2009) reviewed 70 systems available for crop protection in Europe: 18 for diseases in horticultural and fruit crops, 37 for diseases in arable crops, 18 for arthropod pests, and 9 for weeds, with some systems addressing multiple pests.

3 Have DTs really contributed to promoting IPM in practice?

Because of the diversity of systems, crops, and uses, and because of their local relevance, the users' access to DTs (e.g. farmers, agricultural advisers, and policy-makers) has been fragmented and restricted to particular areas and users' groups. The value of a given DT in a range of agricultural contexts and climates is therefore hard to assess. If these DTs are properly mobilized, their use and effects could be substantially increased. Indeed, a number of these DTs could potentially be used in climatic areas and agricultural circumstances that are much wider than their current range of use (Damos, 2015; Rossi et al., 2009).

DTs for crop protection have faced and are still facing (Matthews et al., 2008; McCown, 2012) the so-called problem of implementation, i.e. a "lack of sustained use" (McCown, 2002). In particular, the direct use of DTs for crop protection by farmers has been limited, while the main use has been indirect via agricultural advisors (Been et al., 2009). Jones et al. (2010) used the term "super users" to describe those office employees who access the systems for several weather stations and then distribute model outputs to people implementing the IPM on tree fruits.

Thorough analyses of the reasons for non-adoption and failure of DTs in agriculture have been carried out by several authors, who in turn reflected on the possibility of correcting past errors (Ascough et al., 2010; Hochman & Carberry, 2011; Kerr, 2004; Magarey et al., 2002; Matthews et al., 2008; McCown, 2002; Parker & Campion, 1997; Secher, 1993).

Under-use of IPM DTs has been attributed to (i) technological limitations of DTs and to (ii) farmer perception (Gent et al., 2011; Matthews et al., 2008). Many of the technological problems during the 1990s have been significantly reduced by the increased availability of personal computers, by the increased access to the Internet, and by the development of web-based platforms (e.g. Jones et al., 2010). Despite the development and diffusion of information and communication technologies (ICTs) over the last decades, and even though the current generation of farmers is adopting computers at the same rate as the general public in Western Europe (Ascough et al., 2010), some limitations remain. Attention has been paid during the last decade to the importance that the potential users give to the role ICT systems in decision-making (Matthews et al., 2008). According to Matthews et al. (2008), DT providers focused too much on technological factors rather than on ensuring that the tools developed were credible and useable by farmers. Kuehne et al. (2017) developed a quantitative model that defines 22 factors influencing the adoption of innovations in agriculture. These factors can be grouped according to (i) the characteristics of the proposed new practice, its comparative advantages over current practices, and the ease/speed with which the new practice can be learned, (ii) the characteristics of the population targeted to adopt the new practice with respect to perceptions of the new practice, and (iii) the characteristics of the potential adopters that influence their ability to learn about the practice. Rose et al. (2016) investigated the factors affecting the uptake and use of DTs by farmers and advisers in the UK; these authors identified 15 factors that significantly influenced the adoption of IPM DTs by farmers and advisers. These included the usability, the cost-effectiveness, the performances, the relevance to user, and the compatibility of the new practice with compliance demands. An innovative approach is clearly needed to foster a more sustained use of IPM DTs; the development of ad hoc web-based platform is one such approach.

4 Sharing IPM DTs through a web-based platform

The sharing of IPM DTs should increase wide access to existing knowledge, promote the incorporation of IPM solutions in existing production systems, and increase the support for better plant health policies. The Coordinated Integrated Pest Management in Europe project—a forum for exchange and identification of IPM research and development priorities—concluded that warning systems, forecasting models, and DSSs are required for the effective implementation of IPM and that their sharing has a large potential for transnational co-operation aimed at encouraging farmer adoption of such tools.

In this article, we outline an approach to develop a web platform where ready-for-practice DTs are shared and made available for pest management in diverse geographical areas and agricultural contexts. The platform is meant to respond to more complex needs than the use of individual DTs; it is meant to address multiple crop management issues simultaneously, which is what farmers commonly need (McRoberts et al., 2003; Teng & Savary, 1992; Zadoks, 1981). The platform is also meant to help farmers in the daily implementation of IPM practices in complex agro-ecosystems and in applying climate-smart and precision agriculture; i.e. the platform should help farmers "to implement the right action in the right place at the right time" (Gebbers & Adamchuk, 2010). In describing the platform, we refer to examples from

Europe, but the concepts can be easily extended to other agricultural contexts worldwide.

4.1 Why a new web-based platform for IPM decisions?

Platforms incorporating pest models already exist and are provided by public or private entities at local, national, or supranational levels. However, developing a new platform rather than modifying and enlarging an existing one has clear advantages. As illustrated in Fig. 1 in the form of a SWOT (strengths, weaknesses, opportunities, threats) analysis, the "strengths" and "opportunities" of developing a new platform are greater than the "weaknesses" and "threats". Weaknesses and threats can be easily minimised through the proper management of the platform. Important strength elements include the possibility to customize the platform for different users and to promote interactions among the actors that are involved: IPM experts (research and extension centres and personnel, specialists of plant protection organisations, technical advisors of farmer associations and advisor groups; teachers and trainers in high schools and universities); public or private plant protection organisations; and professional users (farmers, public and private agricultural advisers, and policy makers). Purposes and benefits of these users are summarised in Table 1.

Another important strength of developing a new decision platform is the possibility of selecting the DTs to be included into the platform based on pre-defined selection criteria, i.e. transparency, accuracy, robustness, and reliable credentials. This is currently of paramount importance, because an increasing number of platforms are being proposed to farmers, which represent a threat for IPM (i.e. a loss of confidence) if DTs are unreliable. Unreliable DTs not only cause direct harm to users (e.g. farmer) due to inaccurate output (e.g. disease level, crop loss), but also cause indirect harm since farmers' scepticism reduces further technology adoption.

Developing a new platform also enables the use of "open-source" and "knowledge sharing" approaches, so that knowledge (i.e. information, skills, or expertise) is made available and exchanged among individuals and organizations. The development of a new platform furthermore increases flexibility and scalability, i.e. including new DTs, improvement of existing ones, and their extension to new contexts (countries, regions, crops, and cropping systems).

4.2 Which agricultural areas should be considered?

The platform should include the diversity of environmental contexts of the area of interest. This not only determines platform characteristics (e.g. relevant crop/pest combinations, and DTs to be included) but also delineates the diversity of the agricultural systems and climates to be addressed. The latter influences the sharing of DTs and determines their uptake by users (similar environments, contexts of DT validation, current use). Indeed, the agricultural areas where a DT has already been validated and is in current used greatly affect its future use.

Maps describing agricultural and technological diversity should directly be incorporated into the platform. For instance, the following maps are relevant for Europe: (i) the 78 European nomenclature of agriculture statistical territorial units (NUTS; https://ec.europa.eu/eurostat/web/nuts/nuts-maps); (ii) the EU guidance document on zonal evaluation and mutual recognition of PPPs and the EPPO (European and Mediterranean Plant Protection Organization) guidance on comparable climates for determining comparability of climatic conditions between geographical areas for efficacy evaluation trials on PPPs (Standard PP1/241-1); (iii) the division of Europe into zones with similar pesticide

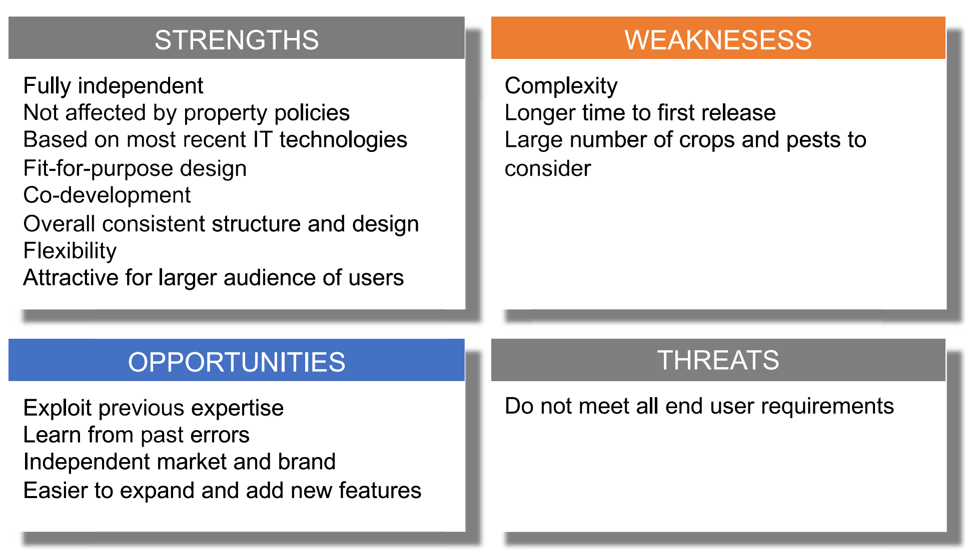

Fig. 1 Strengths, weaknesses, opportunities, and threats of developing a new platform for sharing decision tools for IPM, rather than modifying/enlarging an existing platform

Table 1 Categories of end-users of the platform for sharing decision tools for IPM, their main activities on the platform, their main purposes for using the platform, and the benefits that they can gather

User categories	Main activities	Main purposes	Main benefits
I - IPM experts			
- Researchers - Extensionists - Advisors (expert) - Technicians	• Search DTs • Download materials • Develop DT-based IPM practices • Validate DTs in specific agricultural contexts, and propose adaptation if needed	• Research • Extension • Demonstration	• Expand the range of DT use • Update the Platform • Publish results • Increase awareness of farmers on the IPM toolbox • Increase IPM uptake by farmers
- Teachers - Trainers	• Search DTs • Download materials • Access the DT (graphical) output through UI	• Education	• Improve teaching materials • Increase awareness and knowledge in future generations of IPM actors
II - Information and service providers (having a property Information Technology systems)			
- Private service/advice providers (e.g. consultant companies) - Private device/product providers (e.g. retailers of weather stations) - Public service/advice providers (e.g. Plant Protection Organizations, agricultural extensionists)	• Define DTs of interest • Access the DT (numerical) output though Application Programming Interfaces • Insert the output in own platforms	• Business (for private companies) • Service provision (for public entities)	• Increase the portfolio of DTs • Increase the quality of the offer (reliable DTs) • Increase business opportunities • Increase IPM uptake by farmers
III - Professional users			
- Farmers	• Search DTs of interest • Access the DT (graphical) output though platform dashboard	• IPM implementation	• Increase IPM uptake • Increase knowledge and expertise • Reduce PPP usage • Reduce production costs
- Private agronomists, consultants - Public advisors and warning services (not having a property platform)		• Advice provision	• Increase knowledge and expertise • Increase working opportunities and capacities • Increase IPM uptake by farmers
- Policy makers		• Definition of policies	• Define fit-to-purpose actions • Increase awareness of farmers on the IPM toolbox • Increase IPM uptake by farmers • Reduce negative impacts

effectiveness and environmental effects based on climatic, soil, and crop structure (Lopatka et al., 2016); and (iv) the 1-km^2 resolution map (84 strata and 13 environmental zones) of environmental stratification of Europe developed by Metzger et al. (2005).

4.3 Which combinations of crop and pest are relevant?

The crop/pest combinations to be first considered should be those for which IPM solutions are most urgently needed. Prioritization of crop/pest combinations can be based on the following criteria: (i) crop importance (economic and social/cultural); (ii) importance of pests; (iii) impact of pests and of current pest management on farm income, local and national economy, agri-food chains, human health, and the environment; (iv) current pesticide use; (v) hazards generated by those pesticides that are currently being used; and (vi) risks of emerging pests.

Based on these criteria, a preliminary list of crop/pest combinations for the most economically valuable crops in Europe is given in Table 2, in which over 80 crop/pest combinations are listed by the SHARE4IPM consortium. These crops are also relevant because of their associated use of plant protection products: the total amount of plant protection products sprayed on these crops in 2019 was 272,120 tons of active ingredients, i.e. 76.6% of the total plant protection products used in the EU (EUROSTAT, 2023).

4.4 Which IPM decision tools should be incorporated in the decision platform?

DTs for IPM may support three kinds of decisions (Rossi et al., 2012, 2019): strategic, tactical, and operational. 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). Strategic decisions pertain to crop production in a landholding as a whole, including the production goals and

Table 2 List of the top crop/pest combinations for which IPM solutions are urgently needed in Europe; listed in bold are the 64 pests for which DTs are available in the literature

Crop		Pests for which IPM solutions are urgently needed
Cereals	Barley, oats, rice, wheat	*Avena fatua*, ***Blumeria graminis f.* sp. *hordei and f.* sp. *tritici*, *Drechslera tritici-repentis*, *D. teres***, *Eurygaster integriceps*, ***F. culmorum*, *F. graminearum*, *F. langhsetiae*, *F. poae*, *F. sporotrichoides*, *Pyricularia oryzae***, ***Puccinia recondita*, *P. graminis*, *P. striiformis***, ***Septoria tritici*, *S. nodorum*, *S. avenae*,** *Gaeumannomyces graminis, Sitobion avenae, Shlorops pumilionis, Ramularia collo-cygni*, ***Rhynchosporium secalis***
Maize		***Aspergillus flavus*, *Fusarium graminearum*, *F. langsethiae*, *F. verticillioides*, *Helicoverpa armigera***, ***Ostrinia nubilalis***, *Oscinella frit, Setosphaeria turcica, Tanymecus dilaticollis*
Oil seed	Rapeseed & other oilseeds	*Dasineura brassicae*, ***Ceutorhynchus assimilis***, *Leptosphaeria maculans, Meligethes aeneus*, ***Myzus persicae***, ***Sclerotinia sclerotiorum***
Potatoes		***Agriotes sputator*, *Leptinotarsa decemlineata*, *Phytopthora infestans***
Sugar beet		*Aphids*, ***Cercospora beticola***
Vegetables	Carrots, tomatoes	*Alternaria dauci*, ***A. solani*, *Phytopthora infestans*, *Tuta absoluta***
	Beans, chickpeas, & others	***Ascochyta* spp.,** *Alternaria alternata*, ***Bruchus rufimanus***, ***Colletotrichum* spp.**, *Didymella rabiei*, ***Uromyces phaseoli***
Grapes		***Botrytis cinerea*, *Drosophila suzukii*, *Erysiphe necator*, *Guignardia bidwellii*, *Lobesia botrana*, *Planococcus ficus*, *Plasmopara viticola*, *Scaphoideus titanus***
Olives		***Bactrocera oleae***, ***Colletotrichum* spp.**, ***Fusicladium oleaginum***, *Philaenus spumarius, Pseudocercospora cladosporioides, Pseudomonas savastanoi* pv. *savastanoi*
Fruit trees	Apples, peaches, pears, plums, cherries	*Cacopsylla pyricola*, ***Cydia pomonella*, *C. molesta*, *C. funebrana***, ***Erwinia amylovora*,** *Halyomorpha halys, Hoplocampa minuta*, ***Monilinia fructicola*, *M. laxa*, *M. fructigena*,** *Psylla pyri, Quadraspidiotus perniciosus*, ***Taphrina deformans***, ***Venturia inaequalis***, ***V. pyrina***
Other crops	Almonds & other nuts, currant, strawberries & other small berries, persimmons, pomegranate	***Alternaria alternata***, ***Botrytis cinerea***, *Colletotrichum* spp., *Monilinia* spp., *Dialeurodes citri, Mycosphaerella ribis, Stigmina carpophila, Xylella fastidiosa*
	Citrus fruits	*Ceratitis capitata, Diaphorina citri, Quadraspidiotus perniciosus, Xylella fastidiosa*
Multiple crops	Arable crops	*Chenopodium album, Echinochloa crus-galli, Poa annua, Alopecurus myosuroides*

the production means. A farm may for instance be converted to organic production. Such strategic decisions are often guided by market opportunities and constraints, and are usually made by landholder or farm manager/administrator.

Tactical decisions (e.g. whether and when the crop requires protection, and which protection action is required) are made by crop managers day-to-day in response to what is happening at the crop level (such as a disease outbreak that requires control actions). Operational decisions involve application aspects (e.g. the tractor speed during a fungicide treatment) or a rapid response to unexpected events (such as the decision to postpone the fungicide treatment because of wind). These operational decisions are mainly made by farm workers who implement crop protection measures. All these decisions are relevant in IPM (Rossi et al., 2012) and should therefore be included in the platform. DTs to be included can be any tool, irrespective of the approach used for its development (experimental or model-based), provided that it has been validated (i.e. is or is about to be used by farmers in a given location). A DT that has not yet been validated through farmer's practice may be included in the decision platform if it concerns the only option available for a priority crop/pest combination, and as long as it does not prevent IPM implementation.

Specifically, the DTs should have the following characteristics:

i. To provide basis for decisions on whether prevention (e.g. use of resistant cultivars) and/or suppression/sanitation measures (e.g. crop rotation, residue management, or tillage) are required; for instance, a DT tool may predict possible soil or crop residue infestation.
ii. To provide basis for decisions on whether and when it is necessary and profitable to protect the crop (e.g. prediction of infection periods, of relevant pest devel-

opment stages, or of relevant crop losses, including qualitative losses and contamination by mycotoxins).

iii. To make use of action or economic thresholds (e.g. crop-loss models, pest population thresholds).
iv. To help improve pest monitoring (e.g. prediction of the likely onset of an epidemic or first adults in insect traps) and in food products (e.g. private or public monitoring programs for mycotoxin contamination).
v. To guide choices of plant protection products (e.g. preventative vs. curative fungicides, insect or plant stage-dependent insecticides or herbicides).
vi. To provide details on the correct dose of pesticide to be used (e.g. crop-adapted sprays).
vii. Provide information on the duration of pesticide efficacy after its application.

The number of already available DTs that would meet the above criteria is impressive. For instance, Table 3 lists over 200 such DTs, which concern 32 crops grown in fields, orchards, or greenhouses, and 155 pests. The MOPEST project (Models for pest epidemiology: review, documentation, and evaluation for PEST risk analysis) produced an inventory of about 200 models predicting the establishment, development, and/or spread of quarantine pests (Rossi et al., 2009). A recent systematic literature search (Fedele et al., 2022) retrieved published articles on specific plant-pest models for over 500 fungi, 101 chromista, 48 viruses, 17 virus vectors, and 44 bacteria. This body of literature concerns over 100 different crops, while an additional 51 articles were classified as generic.

Willocquet et al. (2018) developed a generic reverse-modelling approach enabling the computation of crop losses caused by pests. This approach enables the modelling of individual and combined pest (pathogens, animal pests, and weeds) injuries on wheat and can be expanded to other arable crops (Table 4). A general model has been developed enabling the estimation of fungicide dynamics within a crop canopy after application (Caffi & Rossi, 2018), while calculators are available to compute doses of plant protection products to be applied based on the volume of the crop canopy to be protected rather than on the acreage of the crop, known as tree row volume and leaf wall area (Walklate & Cross, 2010).

5 Platform structure and functions

The design of the platform should use a co-development and participatory approach to ensure that the needs of the three above categories of end-users are met. End-users have different expectations about how the platform should work and assist their decisions (Table 1).

The platform described here is meant to be developed as an Internet-based portal, using the *cloud computing* paradigm (Shawish & Salama, 2013). This paradigm implies that the platform provides ubiquitous access to shared pools of configurable system resources and higher-level services that can be rapidly provided with minimal management effort over the Internet. Input/output data storage will also involve *cloud storage*, in which digital data are stored in logical pools and in multiple servers. We describe below the main components of such a platform (Fig. 2).

5.1 Platform engine

The *DT engine* is the core element of the platform. It receives a request from an end-user (through an interactive *User Interface*, UI) and run one or more DTs relevant for the area of interest, which can be selected by the user through the search facilities of the *DT repository*. After receiving the request, the *DT engine* calls the DT(s) from the *DT Hosting Infrastructure*, which is the cloud infrastructure that integrates different remote systems where the DT software tools are operated. The DT software accesses the input data necessary for the DTs to operate in the *DT input management system*, via application programming interfaces (APIs). The *DT engine* finally receives via application programming interfaces the numerical output, which is made available to the user via the UI with a dashboard and in multiple formats (raw data, tables, icons, graphs, and maps).

5.2 User interface

The *user interface* (UI) is the tool enabling to consult and navigate the platform. Given that professional users, and especially farmers, are usually not expert users of ICT solutions, the UI needs to be intuitive, easy-to-use, multi-language, and accessible via all mainstream interfaces (computers, tablets, and smartphones). For this purpose, user experience principles (Walton, 2015) need consideration in developing the UI.

5.3 Repository of DTs

The *DT repository* contains the available DTs for different pest/crop combinations. All DTs included in the repository must be based on explicit, reproducible methods. This is reflected by a series of descriptors (metadata), such as model subject, pests, plants, keywords/descriptors, geographic and temporal coverage, technical specifications (as indicated below), type of DT, model specifications, input and output data, and DT evaluation and application(s). Definition of metadata should be based on international standards and codes, whenever possible, such as CAMASE, ECOBAS,

Table 3 Decision tools (DTs) for IPM that have been validated and are being used in specific areas of Europe

Crop	N. of pests	N. of DTs	Pest/mycotoxin names
Almond	7	7	*Alternaria alternata*, *Eurytoma amygdali*, *Monilinia fructicola*, *Myzus persicae*, *Taphrina deformans*, *Tetranychus urticae*, *Wilsonomyces carpophilus*
Apples	5	9	*Argyrotaenia pulchellana, Cydia pomonella, Erwinia amylovora, Pandemis cerasana, Venturia inaequalis*
Asparagus	1	1	*Stemphylium vesicarium*
Barley	12	17	*Blumeria graminis, Deoxynivalenol (DON), Drechslera teres, Fusarium avenaceum, F. culmorum, F. graminearum, F. langhsetiae, F. poae, F. sporotrichoides, Microdochium nivale, Puccinia hordei, Rhynchosporium secalis*
Blackberries	1	1	*Drosophila suzukii*
Cherries	2	2	*Drosophila suzukii, Monilinia fructicola*
Cucurbits	3	4	*Golovinomyces orontii, Podosphaera xanthii, Pseudoperonospora cubensis*
Eldelberry	1	1	*Drosophila suzukii*
Flowers (cut)	1	1	*Botrytis cinerea*
Grapes	10	19	*Aspergillus carbonarius, Botrytis cinerea, Drosophila suzukii, Erysiphe necator, Guignardia bidwellii, Lobesia botrana, Ochratoxin A, Planococcus ficus, Plasmopara viticola, Scaphoideus titanus*
Kiwifruit	1	1	*Pseudomonas syringae* pv. *actinidiae*
Legumes	10	10	*Ascochyta rabiei, A. pinodes, Alternaria alternata, Bruchus rufimanus, Colletotrichum lindemuthianum, C. lupini, Cydia nigrana, Helicoverpa (=Heliothis) armigera, Sitona* sp., *Uromyces phaseoli*
Loquat	1	1	*Fusicladium eriobotryae*
Maize	16	19	Larvae and adults of *Agriotes lineatus, A. obscurus, A. sordidus, A. sputator, Aspergillus flavus, Chaetocnema pulicaria, Diabrotica virgifera, Fusarium graminearum, F. langsethiae, F. verticillioides, Ostrinia nubilalis, Penicillium* spp., Aflatoxins, Fumonisins, DON, T2/HT2
Oats	1	1	DON
Oilseed rape	5	5	*Brassicogethes aeneus, Ceutorhynchus napi, C. pallidactylus, Psylliodes chrysocephalus, Sclerotinia sclerotiorum*
Olives	2	6	*Fusicladium oleaginum, Bactrocera oleae*
Onions	1	2	*Peronospora desctructor*
Peaches	9	13	*Adoxophyes orana, Anarsia lineatella, Cydia molesta, Monilinia fructicola, Monilinia* spp., *Sphaerotheca pannosa, Taphrina deformans, Wilsonomyces carpophilus, Xanthomonas arboricola*
Pears	6	8	*Argyrotaenia pulchellana, Cydia pomonella, Erwinia amylovora, Pandemis cerasana, Stemphylium vesicarium, Venturia pirina*
Pistachio	1	1	*Septoria* spp.
Plums	2	2	*Cydia funebrana, Drosophila suzukii*
Potatoes	9	18	Larvae and adults of *Agriotes lineatus, A. obscurus, A. sordidus, A. sputator, Alternaria alternata, A. solani, Leptinotarsa decemlineata, Phthorimaea operculella, Phytophthora infestans*
Raspberries	1	1	*Drosophila suzukii*
Rice	5	5	*Cochliobolus miyabeanus, Pyricularia oryzae, Rhizoctonia solani*, Rice Tungro S and B viruses, *Xanthomonas campestris* pv. *oryzae*
Rye	3	3	*Puccinia recondita, Blumeria graminis, Rhynchosporium secalis*
Strawberry	1	2	*Botrytis cinerea*
Sugar beet	2	8	*Erysiphe betae, Cercospora beticola*
Tobacco	1	1	*Peronospora tabacina*
Tomatoes	7	11	*Alternaria solani, Helicoverpa (=Heliothis) armigera, Oidium lycopersici, Phthorimaea operculella, Phytopthora infestans, Pseudomonas syringae, Xanthomonas campestris pv. vesicatoria*
Triticale	6	6	*Puccinia triticina, P. striiformis, Blumeria graminis, Rhynchosporium secalis, Parastagonospora nodorum, Zymoseptoria tritici*
Wheat	22	31	*Blumeria graminis,* Barley Yellow Dwarf Virus (BYDV), *Fusarium avenaceum, F. culmorum, F. graminearum, F. langhsetiae, F. poae, F. sporotrichoides, Microdochium nivale, Parastagonospora nodorum, Puccinia recondita, P. striiformis, P. triticina, Pyrenophora tritici-repentis, Rhopalosiphum maidis, R. padi, Sitobion avenae, Zymoseptoria tritici*, DON, Nivalenol (NIV), Trichothecene mycotoxins (T2-HT2), Zearalenone (ZEA)

Table 4 Crop and pest combinations for which yield-loss models have been developed

Crop	Pests
Wheat	Aphids: *Sitobion avenae*
	Powdery mildew: *Blumeria graminis*
	Brown rust: *Puccinia triticina*
	BYDV disease: Barley Yellow Dwarf Virus
	Eyespot: *Oculimacula acuformis*; *Oculimacula yallundae*
	Fusarium head blight: *Fusarium avenaceum*, *F. culmorum*, *F. graminearum*, *F. poae*, *Microdochium nivale*
	Fusarium stem rot: *Fusarium graminearum*, *F. culmorum*, *Microdochium nivale*
	Septoria nodorum: Stagonospora nodorum
	Septoria tritici: Zymoseptoria tritici
	Sharp eyespot: *Rhizoctonia cerealis*
	Take-all: *Gaeumannomyces graminis* var. *tritici*
	Yellow rust: *Puccinia striiformis*
Rice	Bacterial leaf blight: *Xanthomonas campestris* pv. *oryzae*
	Sheath blight: *Rhizoctonia solani*
	Brown spot: *Cochliobolus miyabeanus*
	Sheath rot: *Sarocladium oryzae*
	Leaf and neck blast: *Pyricularia oryzae*
	Dead heart and white head caused by several stem borers: *Scirpophaga incertulas*, *S. innotata*, *Chilo suppressalis*, *Sesamia inferens*
	brown plant hoppers: *Nilaparvata lugens*
	various leaf-feeding insects: for example, *Cnaphalocrocis medinalis* and *Hydrellia philippina*

PestCast, CREM, Content Standard for Computational Models, and MOPEST (Table S1, Rossi et al., 2009).

The *DT repository* therefore contains metadata of each DT, including the required input data and data measurement methods, including weather and crop data if required. Some of these inputs are field-specific (e.g. previous crop, characteristics of the variety sown) and are to be entered by the users when calling a given DT; others depend on the geographical area (e.g. weather) and are to be managed automatically by the "DT input management system". Metadata makes the selection of DTs relevant to user's needs through the *UI*, since users searching DTs for their own purpose enter specific keywords and search criteria (including the geographic areas where DTs have been validated).

5.4 Management system for DT input data

The *DT input management system* provides components for integrating a range of public and private, current and forecasted, weather data, together with other input data (e.g. soil), as well as geographic and crop resources, so that the required data are mobilised by the platform to compute DTs. This component is likely to access to customised or proprietary data (e.g. private networks of weather stations). Given the heterogeneity of information to be integrated, these data need to be translated into a common format (the *Input Data Format*) prior to entering the platform. Interoperability of input data will be enhanced if well-established data formats are used (some examples are provided in Table S1). This component of the platform also has to address differences among variables measured, including data acquisition time-steps (e.g. hourly vs. daily), precision and accuracy of sensors, data quality checking routines, and missing data management. Advanced *data quality control* procedures are therefore required to ensure consistency among measurements, their consistency with weather and climate data, or again spatial and temporal consistency. Machine learning and pattern recognition techniques to automatically detect anomalous data patterns (Omar et al., 2013) should be considered.

5.5 Hosting infrastructure for DTs

The *DT Hosting Infrastructure* enables the platform to interact with the DTs encoded in third-party systems, i.e. DT providers (Fig. 2). This component receives a call from the *DT engine* via application programming interfaces requesting to run a given or several DTs, as well as the input data required to run the DT via the *DT input management system*. Cloud computing and the platform structure thus enable a third-party system to run the DT and to produce numerical outputs that are returned to the DT engine, which in turn generates a new output towards the end-user through the *UI* in the form of a dashboard.

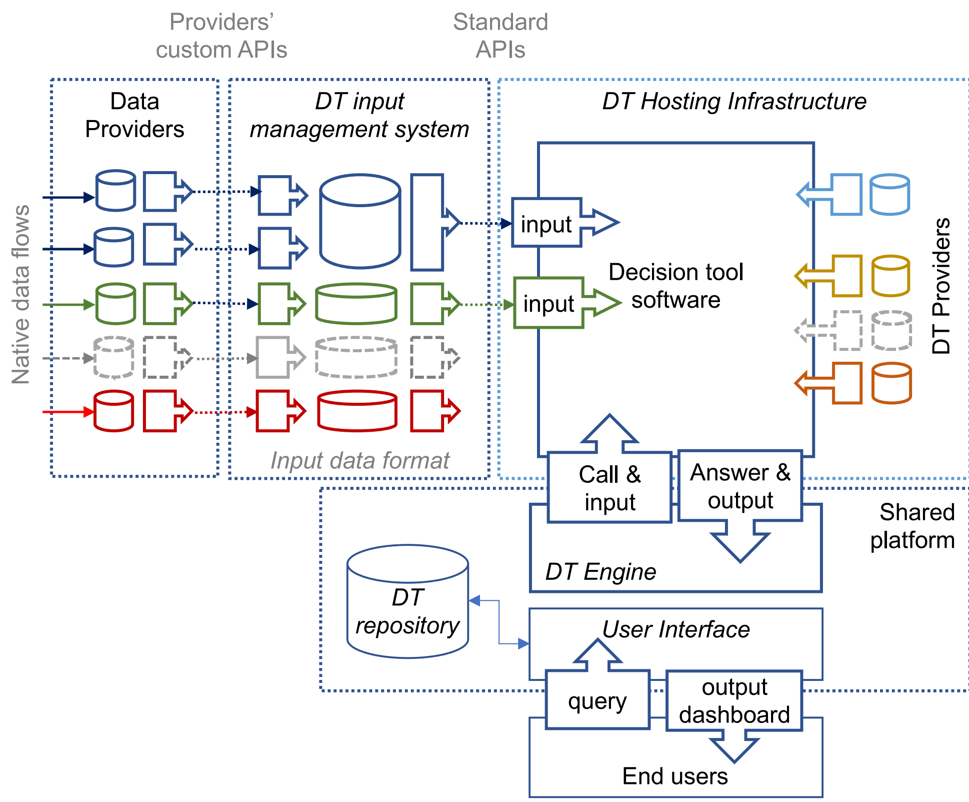

Fig. 2 Main architecture of the platform for sharing decision tools for IPM; application programming interfaces (APIs) and decision tool (DT) components are illustrated

5.6 Data flow component

The *data flow* component enables communication between the different components of the platform (Fig. 2). The platform operates an on-demand (synchronous) workflow, while activities requiring substantial computing time can be performed asynchronously.

6 How users can benefit from the platform

The three categories of end-users ("IPM experts", "information and service providers", and "professional users") access the platform with different purposes (Table 1). Some examples are provided below.

6.1 IPM experts

IPM experts could use the platform to search for DTs of interest, to download the documentation regarding the DT, to contact the DT provider for further explanations, to validate the DT for specific agricultural contexts, and to propose modifications/adaptations when needed. For instance, an extension agent can envisage that the IPM program for a crop in his/her area of interest would benefit from a DT. The agent should then access the platform and find a DT that could be useful for the purpose, and verify whether the tool has been validated in the specific area. If the tool has not been validated, the agent could organise a validation, and download the material needed to compare the current and DT-based IPM practices. In case the DT requires adaptation, the IPM expert should contact the DT maintainer (who should be indicated in the metadata of the *DT repository*) and discuss the required modifications.

6.2 Information and service providers

These end-users hold property ICT systems providing DT-based alarms/advice to professional users, and can be private companies (e.g. producers of weather stations, agrochemical companies, and software producers) or public entities. These end-users are connected with the platform via application programming interfaces (APIs) to the DTs of interest, receive back the DT (numerical) output, and finally integrate it into the dashboard of their systems. These end-users usually lack in-house expertise with DTs and embed (simple) models from the literature into their web systems without (sufficient) validation. Providing these end-users with access to reliable models via the platform may increase the quality of the information they provide to clients.

6.3 Professional users

These end-users access the platform to search for DTs of interest and examine the DT output directly through the platform dashboard for decision-making. The platform may also help public authorities manage IPM requirements. For instance, public authorities could use the platform to decide whether it is convenient to enable the use of a PPP that is not permitted within IPM protocols in those areas in which the risk for the development of a specific pest is extremely high.

7 How does the platform address the "implementation problem"

7.1 Addressed problems

DTs often concentrate on a single problem, whereas farmers face a wide range of problems at the farm scale (e.g. Magarey et al., 2002; Parker & Campion, 1997; Rossi et al., 2009; Savary et al., 2018). As described in Section 4.4, the platform should include multiple DTs concerning the main pests of a crop, thus enabling holistic decision-making, and all main requirements for practical implementation of IPM, to assist farmers with both daily operational and long-range strategic decisions. Participatory educational approaches (Roling & Wagemakers, 1998) may help scientists recognize that their goals may not align with those of the end-users: "Indeed, lack of education of IPM developers about the perceptions of farmers is probably a much greater obstacle to implementation than the reverse" (Wearing, 1988). Involvement of the potential users during DT development is then a way of limiting implementation issues (e.g. Igbaria & Guimaraes, 1994; McCown, 2012; Oliver et al., 2012). We recommend that the platform be developed in close collaboration with multiple user categories to ensure that the needs of all users are addressed.

7.2 Quality of output

The quality of information and advice provided to end-users by some DTs is sometimes poor. This stems from the ease of electronic communication and information delivery, resulting in some DTs being pushed into service before having been sufficiently checked and validated. Communication between developers and users is often poor, leading to lack of refinement of DT products. This is particularly true for commercial systems (Magarey et al., 2002). An effective IPM platform must contain DTs that are ready-for-practice, i.e. those that have been validated and commonly used in some agricultural contexts.

7.3 User-friendliness

Many agricultural DTs lack a user-friendly interface: this is a major obstacle to their use. Farmers typically require simple, clear, and concise information. Farmers usually do not react well when delivered large amounts of redundant, complicated information, some of which they do not even need (Ascough et al., 2010). Worm et al. (2010) showed that the acceptance of a DT increases with its improved "look and feel". Historically, many DTs reported outputs in quantitative terms, which growers find difficult to interpret: based a number, a grower still has a decision to make. The platform dashboard should be co-designed with end-users. It may include simple symbols showing the levels of risk associated with a management option (Magarey et al., 2002).

7.4 Time required to operate and obtain information

The time demand put on the individual end-user to learn and use the system can be—and probably is, because this learning time covers many of the IPM bottlenecks (Jeger, 2000)—the single most important factor in the success or failure of a system (Travis & Rajotte, 1995). Using many systems require too much time because of delays in data processing, or because of tedious input requirements (see, e.g. the case of GPFARM; Ascough et al., 2010). Users, for instance, should not need to manually select the input information sources from a long list (e.g. weather stations, sensors); this selection should instead be proactively assisted by the platform with a preselected list of sources.

Many crop management decisions cannot be postponed at the farm day-to-day operations. The platform therefore must be synchronised with the grower's time interval when decisions must be made. Grapevine growers for instance usually use a half-day interval for decisions about downy mildew control. Decisions are made for this morning, this afternoon, or tomorrow morning. For such growers, near real-time advice must be generated, based on real-time and forecast weather data, and this is needed 24/7: epidemics do not (and farmers cannot) have breaks for the weekend.

7.5 Maintenance and updating

Modern software and cloud computing networks are expensive to develop and maintain. The construction of a DT often requires time and financial investments generated by projects with adequate financing. When maintenance is not adequately supported, there are often little resources left for DT maintenance and updating. Maintenance costs may be provided in the form of fees paid by users. Jones et al. (2010) estimated the fee for a DT for tree fruit IPM on the basis of the number of current users and maintenance and training costs. The calculated fee grower benefits resulting from use of the DT were not included. The platform we developed is designed in such a way that the DTs are regularly maintained and updated by DT providers as part of their own regular work.

7.6 Farmers want to participate in decision-making

Many DTs have been unsuccessful because growers had the feeling of not participating in the decision process (McCown, 2002). Rather than making decisions on behalf of users by prescribing a course of action as "the best" solution, the system should instead attempt to help end-users to make their own choices in a complex and uncertain reality (Hochman & Carberry, 2011; McCown, 2002). The platform should thus function as a tool that provides the information required by users to implement their own decision-making process (McCown, 2002; Secher, 1993). In other words, the platform should not be meant to replace the user's decision process.

7.7 Gaining end-users' trust

Another factor influencing the adoption of a system is its practical impact and market credentials (Stone & Hochman, 2004). The introduction of an information technology system for crop management represents a "sustaining innovation", which requires a significant change in practice (and behaviour; McCown et al., 2009). To use a DT, potential users therefore need to recognize the relevance of the DT in their activities and the benefits it may generate (McCown et al., 2009). A tool can gain a farmer's trust through trustworthy independent opinion and through observation of its use by peers.

7.8 Demonstration of benefits

The economic benefits resulting from the use of DTs have been demonstrated in only a few cases. Caffi et al. (2010, 2012) conservatively estimated that the use of mathematical models to manage powdery and downy mildews in viticulture reduced pesticide applications by 30%. This represents a 150 €/ha cost reduction per year. DTs have however not been widely used even when their economic benefits have been demonstrated (Gelb, 1999; Parker & Campion, 1997). Kuhlmann (1999) offered an economic explanation: farming costs are simply more effectively lowered by reducing production inputs, purchasing cheaper inputs, and simplifying farm operations than by using DTs.

Therefore, DTs should be assessed based on overall sustainability (i.e. economic, environmental, and social sustainability) rather than only on immediate economic benefits. The advantages of using DTs may be manifold. A few examples follow:

1. The application of a DSS in Italy for durum wheat generated a carbon footprint of 0.61 t CO_2 equivalent/t wheat yield, representing a reduction of 16% compared to the common practices (Ruggeri et al., 2022). If this reduction occurred over the EU, more than 60.3 million tonnes of CO_2 equivalents per year, i.e. 1.3% of total European greenhouse gas emissions.
2. Caffi et al. (2017) and Pertot et al. (2017) showed that the application of DT-based IPM practices in vineyards and pear orchards increased social sustainability. The sole application of DTs reduced the health risks for agricultural workers and made the production system more acceptable to consumers and society.
3. DTs can also help agriculture achieve several of the Sustainable Development Goals (SDGs) set by the United Nations. DTs may (1) help end hunger (SDG 2) by increasing crop yields by decreasing in pre-harvest losses, (2) increase human health and well-being (SDG 3) by reducing pesticide use, (3) help farmers achieve sustainable economic growth (SDG 8), (4) foster innovation (SDG 9), and (5) help decrease land degradation and biodiversity losses (SDG 15) resulting from pesticide use.

8 Conclusions

In this article, we describe a web-platform that (i) incorporates a variety of DTs for IPM that are ready for practice, i.e. they are available, validated, and already used in some agricultural contexts, (ii) provides open, full documentation of DTs, (iii) makes DTs available for validation and adaptation in different geographical areas and agricultural contexts, and (iv) makes DTs easily available for multiple kinds of end-users.

We are convinced that such a platform could increase farmer awareness of the available IPM toolbox and provide farmers with broader access to the existing knowledge of IPM; more specifically, the platform could provide tools that support the overall decision-making process in crop protection. Among these tools are models and model-based decision support systems that are able to predict whether and when it is necessary/profitable to spray. As mentioned in this article, however, many other tools are available that are able to support the overall decision-making process in crop protection, from pest prevention and suppression to PPP selection, dose definition, and application. The platform we propose should therefore help to make users aware that multiple DTs can be used in an integrated system; the increase in this awareness should increase the possibility that IPM is successfully implemented. The platform may directly support a more sustained implementation of IPM by helping farmers use

DTs and implement IPM practices. The platform may indirectly support a more sustained implementation of IPM by providing advice to farmers from advisors and companies that provide IPM-related services. In both cases, farmers benefit from receiving information generated by robust, validated/adapted DTs. To our knowledge, this kind of platform has not been developed yet. An EC-funded project called IPM Decisions (https://www.ipmdecisions.net) is ongoing and aims to create an online platform for the monitoring and management of pests and to provide farmers and advisers access to a large range of existing DTs for their regional conditions. We believe that this project, and perhaps others in other countries, can benefit from the topics discussed in this article and from the platform we envisaged.

The potential barriers and incentives which determine whether farmers will adopt DT-based IPM practices require further investigation. The Theory of Planned Behaviour (TPB; Armitage & Conner, 2001) can be used to better understand reasons for non-adoption and find leverages to encourage farmers to adopt IPM DTs (see also Escalada and Heong (2012) for an example for the Global South and IPM in rice). Farmers are more likely to adopt DT-based IPM practices (i) if their outcomes, along multiple dimensions that are not limited to economics, are clearly favourable, (ii) if farmers perceive and understand social pressures to adopt such practices, and (iii) if farmers feel capable of, and are enabled to, implement these practices on their farms.

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Declarations

Conflict of interest The authors declare no competing interests.

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