Integrated pest management in temperate horticulture: seeing the wood for the trees

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Abstract

Owing to the decreasing availability of synthetic pesticides, there is an urgent need for developing and improving alternative pest control methods in horticulture. Integrated Pest Management (IPM) aims to reduce and control the damage caused by pest organisms by making use of ecological interactions between the pest, its antagonists and the environment. IPM usually involves combined use of pesticides, pest antagonists, mass trapping and environmental manipulation. This gives rise to potentially negative interference amongst these components as well as with other environmental and crop-related factors. Such interference has the potential to reduce IPM efficacy, especially as the use of IPM is broadened and intensified. Evidence for such interference among components of IPM is briefly reviewed and the need for a research agenda that investigates such interference experimentally is discussed along with the potential for using ‘big data’ generated in IPM to conduct meta-analyses and construct powerful models for IPM. These approaches to research and data management should support the expansion and improvement of Decision Support Systems (DSS) for IPM practitioners that combine databases, expert networks and models. The success of DSS based on increasingly complex and extensive knowledge and data greatly depends on their accessibility, ease of use and whether they produce clear outputs that support decision-making by growers and consultants. The aim must be to improve IPM efficacy, predictability, cost-effectiveness and sustainability, while still finding ways of helping IPM practitioners identify IPM strategies that are optimal for their needs amongst an increasing number of options.

Keywords: Integrated Pest Management, IPM, Horticulture, Decision support systems, Modelling

Review Methodology: I searched the following databases for research articles and reviews: CAB Abstracts, ISI Web of Knowledge and Google Scholar. I used topic-specific search terms (e.g. two-spotted spider mite integrated pest management; horticulture meta-analysis). Since a portion of this review covers web-based databases and tools, I carried out internet searches using search terms related to decision support systems via Google. In addition, I used references from the articles and websites obtained by these methods to check for additional relevant material. I also spoke to colleagues at meetings and conferences on IPM about their views on the topics and issues discussed herein.

Integrated Pest Management (IPM): Brief History and Current Context

Despite over half a century of refinement and widespread use of synthetic chemical pesticides [1], arthropod pests still cause dramatic crop losses in horticulture and agriculture, with an estimated yield loss of US$470 billion dollars annually [2]. Invasive pests threaten to add significantly to this damage, recent examples including spotted wing drosophila (Drosophila suzukii Matsumura, 1931) [3] and the box tree moth (Cydalima perspectalis Walker, 1859) [4] that have rapidly spread in
North America and/or Europe. Suppressing pest populations by manipulating and exploiting ecological interactions between pest, crop and environment predates the use of synthetic pesticides and the dawn of mechanized, modern horticulture and agriculture of the twentieth century [5–7]. Today, the practice of 'integrated pest management' incorporates a wide range of pest control methods and commonly includes synthetic chemical pesticides, biopesticides and antagonistic organisms that suppress pest populations via biological control [7, 8]. As such, IPM is distinct from conventional pest control that relies almost exclusively on the application of synthetic chemical pesticides and has been practiced in most cropping systems for the past 70 years [1]. Additional components of IPM strategies may involve the use of pest-resistant varieties of crops generated via traditional breeding or genetic modification [9, 10], intercropping and other cropping practices [8], environmental manipulation to discourage pests and/or encourage beneficial organisms (e.g. margin vegetation management, physical barriers [11, 12]), mass trapping of pests [13, 14], artificial lighting in glasshouse crops [15] and other methods.

The recent rise in importance and implementation of IPM is mostly a result of the increasing scrutiny of synthetic pesticides and their environmental and human impacts in the past 50 years [6, 16] and increasing concern over pests developing resistance [17]. Current legislation in the EU and internationally is aimed at reducing the use of synthetic chemical pesticides [18] and their availability is declining as a result (e.g. [19]). Consequently, IPM research and practice is in a period of transition as there is an increasingly urgent need for the development of effective pest control methods for use in horticulture and agriculture IPM that is expected to grow for the foreseeable future [20–22].

IPM in Temperate Horticulture: a High Bar for Success

Given the anticipated requirements in global food supply [23] and the often large-scale, industrialized nature of food production in temperate regions [24], IPM strategies in horticulture must meet several key criteria if it is to replace conventional pest control reliant on synthetic pesticides:

(i) Efficacy: IPM should achieve similar or improved pest control efficacy and yield protection compared with the conventional pest control it replaces.

(ii) Reliability and ease of use: Ideally, IPM strategies will perform as reliably and be as easy to deploy as conventional methods.

(iii) Cost/benefit ratio: Assuming equal efficacy, the cost per unit area of application of IPM (including labour, material and land use) should be competitive with that of synthetic pesticides and lower than the value of crop losses it prevents.

(iv) Sustainability: IPM must effectively combat invasive and emerging pests and provide continuing control in the long term. Moreover, the environmental impact of IPM should not exceed that of conventional pest control it is replacing.

In general, integrated cropping systems in horticulture improve sustainability in comparison to production reliant on conventional pest control [25–28] and there are numerous examples of control methods that form part of IPM programmes at various scales (e.g. biopesticides, biological control and mass trapping) being successfully implemented in a variety of cropping systems in temperate regions, resulting in a reduced need for synthetic pesticides (e.g. [29–32]). Biological control organisms and biological pesticides commonly used to replace synthetic pesticides in IPM are currently often less cost-effective than synthetic pesticide alternatives at the time of application, but cost-efficiency has improved in recent years [31] and development costs for control methods used in IPM tend to be significantly lower than for synthetic pesticides [7]. Moreover, valuations of biological control that take into consideration ecosystem services and other secondary benefits suggest that biological control is competitive and sometimes more cost-effective than control using synthetic pesticides [33]. Despite these improvements, the criteria listed above are unlikely to all be met adequately if pest control is viewed in isolation of and not fully integrated with the design and operation of cropping systems. One way of achieving this is by adopting the paradigm of 'Ecological Intensification' for cropping system design and operation [34], where low-impact cropping systems are created by enhancing natural ecosystems through gradual addition of inputs only where absolutely necessary, thereby maintaining ecological processes and naturally integrated pest control mechanisms that make crops in these ecosystems resilient against pests. Expanding IPM in current, highly artificial cropping systems will reduce inputs into these systems and should help move them closer to the scenario envisioned under 'Ecological Intensification', if from the opposite direction. Ultimately, the design and operation of all aspects of cropping systems should also be considered as components of IPM, thereby making the minimization of pesticide use integral to the planning of cropping systems – an example of this approach is the STEPHY guide supporting this approach that was recently produced by the ENDURE Network in Europe [35].

While recent successes illustrate the potential of IPM, there are significant short- and long-term challenges facing researchers, industry and growers that will require innovative approaches to research, development and implementation of IPM methods [5, 22, 24, 36]. 'Integration' should be explicitly understood to mean more than simply substituting individual synthetic pesticides with
biopesticides or alternative pest control methods, as many growers still do [37]. A truly ‘integrated’ pest management programme must consider how these methods interact and complement each other within the framework of a larger IPM strategy that aims to reduce or even eliminate pesticide usage. A consequence of this is that the perceived (and often real) complexity of IPM frequently prevents growers lacking knowledge and/or confidence to effectively implement it [38], especially in developing countries [39]. At the same time, researchers and growers are faced with a deluge of information and data [40] from individual laboratory and field trials that, unless data are managed, analysed and presented wisely, will confuse rather than clarify grower’s choices in IPM and reduce adoption and efficacy of IPM programmes [41, 42]. Indeed, the decision-making process for when and how deploy IPM methods is of core importance, as it largely determines the probability of success [38]. Decisions must therefore not only be based on the best available empirical evidence, but new approaches in IPM research, practice and communication are required – not only to improve IPM in general, but also to help researchers, growers and other stakeholders to see ‘the wood for the trees’.

**IPM: Complex by Nature**

Typically, development of an IPM programme rapidly proceeds from the identification of an emerging pest. Initially, antagonistic organisms and other controls that are potentially useful for management of the pest are identified and tested for efficacy (e.g. [3]). The result is a growing list of broad-spectrum controls (e.g. entomopathogens, biopesticides and synthetic pesticides) and pest-specific controls (pheromone lures, specialist parasitoids, etc.) available for use in IPM programmes. As of October 2014, the European and Mediterranean Plant Protection Organisation (EPPO) listed 97 commercially used biological control agents [43] and the database of the National Sustainable Agriculture Information Service in the USA lists 200 biorationals for use against insect pests [44]. Van Lenteren [45] reports that globally in 2010, 230 species of invertebrate natural enemies were used for augmentative biological control of pests. These numbers are expected to grow in coming decades [8, 20].

IPM is, by its very nature, complex in both theory and practice: if multiple pesticides and/or pest antagonists are used on a single crop, for example, they typically each have their own requirements for timing, dosage and application/release method [38]. Moreover, components of an IPM programme are likely to interact with each other and with the environment [5, 46, 47] (Figure 1).

This presents a stark contrast to past approaches to pest control, in which a small number of broad-spectrum synthetic pesticides were often seen as ‘silver bullets’ [5, 8] that could provide a simple and straightforward solution to pest problems and usually did not require specialist knowledge or equipment for effective application [1]. Thomas [36] has argued that a narrow view of replacing individual pesticides with other singular control methods (e.g. one biopesticide or specialist parasitoid) is not sufficient and that control methods must be fully and extensively integrated if IPM is to be sustainable and efficacious. Such IPM programmes with many components may benefit from ecological interactions between components if they are additive or synergistic [24, 36, 78–80]; for example if one predator facilitates prey capture by another [81]. If, however, the components compete amongst each other for resources (e.g. biological control organisms such as predators, pathogens and parasitoids [82]) or otherwise inhibit each other, this can result in sub-additive or reduced overall efficacy and ultimately failure to control the pest [36]. Here, I will refer to such negative interactions as interference. Of particular concern has been the compatibility of biological control organisms with synthetic and naturally derived broad-spectrum chemical pesticides which are both frequently used in combination in IPM [83–86]. Insecticides may also interfere with other biological IPM tactics, such as the release of sterile insects [87]. Further interference may arise from synthetic fungicides and other synthetic compounds used in crop production to control plant pathogens impacting on beneficial insects used for biological control of pests [88, 89].

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**Figure 1.** Diagram illustrating ecological interactions of the two-spotted spider mite with its host plant and interactions with and among various components of IPM programmes for two-spotted spider mite. Solid lines indicate direct interactions between spider mite and IPM components or host plant and dashed lines indicate indirect interactions among IPM components (interference). Arrows indicate unidirectional and bidirectional interactions. Supporting references are indicated by numbers in boxes. For simplicity, the figure does not include general abiotic factors like temperature and air humidity that will affect most or all of the other biotic and abiotic interactions in the figure (e.g. [31, 46, 68, 77]).
As the number of components in an IPM programme increases the number of possible interactions between these rises exponentially, especially if they are operating at the same trophic level. Though fundamental knowledge of the ecological significance, roles and behaviours of pest control methods used in IPM may guide intuitive predictions on the likelihood of IPM interference, quantifying this effect on multiple trophic levels is not a trivial task. Moreover, interference can occur at a local scale [82] and at a landscape scale [90, 91] and IPM at field and landscape scale may conflict with each other and with conservation goals [92]. Additional complexity arises from interactions of other biotic and abiotic environmental factors with control methods used in IPM [31, 36].

Figure 1 gives an impression of the number and scope of interference and interactions that have been experimentally observed in IPM research on a widespread, phytophagous pest in horticulture, the two-spotted spider mite, *Tetranychus urticae* Koch, 1836 (Trombidiformes: Tetranychidae) [93]. In addition to the multitude of direct interactions between pest, crop, control methods and environment, secondary and multitrophic interactions can also occur [5]. For example, mycorrhizal associations of plants and fungi can improve plant nutrition and crop yield, but also make plants more attractive to spider mites and can increase the mites’ rate of reproduction [55, 71], thus affecting competing interests of the grower. Acaricides (synthetic and biological) not only suppress the pest, but can also impact beneficial predators and other pathogens and pests that may compete or otherwise interfere with the spider mite [88]. Non-crop vegetation can influence prevalence of phytophagous pests and their predators [74]. One could easily imagine an almost infinite number of additional interactions that have yet to be studied or even considered, for example those involving endophytic fungi [94] or the microfauna of the rhizosphere [95]. Complex interactions like these have the potential to affect IPM of the vast majority of pests, even in more controlled glasshouse environments, where multiple pests and pathogens can occur simultaneously [96].

No doubt many of the interactions between IPM components will only have a minor or negligible effect on the overall efficacy of any IPM programme (e.g. [67]), but some have the potential to cause significant interference and thus disrupt pest control [5, 36]. For example, Denno et al. [46] hypothesized that biotic and abiotic interactions in soil that reduce the strength of trophic cascades could explain the occasional failure of biological control with entomopathogenic nematodes. A better understanding of IPM complexity and the impact of interference on efficacy is therefore essential in identifying additional efficiencies in IPM and allowing better predictions about its probability of success and efficacy. Considering this complexity in IPM development and decision-making seems, however, to conflict with the goal of making IPM more accessible and easy to use for growers [38, 42]. Birch and Begg [22] have highlighted this apparent dilemma as the key challenge for IPM development and emphasize the need for ‘IPM Packages’ that are easy to use and offer simple choices when faced with pests, yet also take into account the complexity of biological systems.

**Engaging with the Complexity of IPM: the Need for Large-Scale Trials**

Early stages in the search for effective controls of pests are usually, by necessity, focused on single factors and carried out in a laboratory setting. They are aimed at screening chemical compounds or antagonistic organisms for their potential to kill, attract (for trapping) or otherwise impact on the pest (e.g. [14, 97–100]). Subsequent field trials frequently incorporate combinations of pesticides, biopesticides and antagonists (e.g. [67, 79, 101–103]), or investigate interactions of these control methods with other factors (crop type, pest environment, temperature etc.; [48, 104, 105]). Too often, however, field trials are limited in scale and time due to funding and resource constraints, which means that trials that cover a large geographical scale and multiple crops or pests are comparatively rare (e.g. [47, 106–108]). Long-term studies are similarly uncommon (e.g. [109]) and IPM practitioners are therefore often faced with a patchwork of numerous individual studies that are of limited scale and scope and from which it is difficult to extrapolate to field-scale, long-term IPM outcomes. Finally, due to the common bias against publication of null results [110], pest control methods or full IPM programmes that have ‘failed’ are often not reported in the literature and potential reasons for failure are not always explored. To better encompass the complexity of biological systems in IPM will require a significant investment in large-scale, multi-factorial field trials that, ideally, are consistently monitored over a number of years and widely communicated. For example, Denno et al. [46] have highlighted the need for large-scale, in depth studies of interactions among entomopathogenic nematodes and biotic and abiotic conditions to explain the inconsistency of their efficacy when used in IPM. They also argue that the need for such studies is likely to increase as nematode products are developed that persist in soils for longer after application, thereby increasing the probability of antagonistic interactions in the long term. Lewis et al. [5] draw an analogy between a systems view of agronomical cropping systems and a systems view of the human body in medicine, each consisting of numerous, complexly interacting components. Multi-factorial field trials in IPM can therefore be imagined as the ‘clinical trial’ stage of research and development, helping not only to identify the conditions for effective and sustainable IPM, but also the extent and consequences of ‘side effects’ (i.e. IPM interference or unwanted environmental impacts) [111].

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Field trials of this magnitude and complexity may seem unrealistic given current constraints in terms of funding, manpower and time [7], but it can be argued that work on this scale is already being carried out on a daily basis by IPM practitioners, though the data generated are not being used to their full potential.

Making the Best use of Field Data in IPM: ‘Big Data’ and Meta-Analyses

IPM consultants, practitioners and their professional bodies, during their regular operations and daily activities, are often recording large amounts of field data on IPM that are currently not being used to their full potential [112, 113]. For example, when outcomes of IPM are communicated from growers to consultants, these data may not be formally recorded. These data may then contribute to the experience and expertise of individual consultants and are occasionally relayed at conferences and meetings, but they ultimately remain anecdotal. The internet offers the opportunity to gather, collate and curate raw quantitative and qualitative data from growers (and researchers) in openly accessible databases, an approach that has already revolutionized molecular biology [114]. While such databases are becoming more common in food production industries, they frequently operate at a regional or national level and/or emphasize dispensation of information based on user queries rather than data collection from growers (e.g. [41, 115]).

Depending on the rigour and volume of the data gathered in such databases [113], they could be used as the basis for a wide range of data mining, modelling and other activities. Such efforts will require collaboration and sharing of information between growers, consultants and industry. Modelling based on data from cotton fields in California generated by growers and pest control advisors allowed [116] to identify the effect of previous crop on crop yield and damage caused by the Western tarnished plant bug, Lygus hesperus Knight, 1913. Data from Zespri International, a private limited company owned by over 2500 New Zealand Kiwi farmers, was used to forecast the outcome of leafroller pest monitoring and subsequent control decisions [117]. On a larger scale, the utility of pest trap data from orchards and vineyards around the world in geostatistical analysis that allows mathematical modelling of pest distribution at a landscape scale is summarized by Sciarretta and Trematerra [118]. Making the usefulness of agronomical data in modelling and data mining more visible to contractors, farmers and advisors will help to encourage the collection of big data and increase the willingness to share it.

Integrating and analysing large quantities of data (‘big data’) on an even greater scale, using diverse data sources and collection methods, is anticipated to become increasingly important as a tool in supporting decision-making in food-production [113]. In light of this development, the UK government is investing in the development of a Centre for Agricultural Informatics and Metrics of Sustainability (AIMS) at Rothamsted Research [119]. Also hosted by Rothamsted Research is a new web-based knowledge exchange system called Cropprotect that will collect some basic data from growers using the system [120]. The Voluntary Initiative in the UK hosts an internet portal through which growers can report their IPM plan(s) in accordance with the Sustainable Use Directive of the EU [121]. Portals like this could allow growers to submit data they are recording, for example on pest and beneficial organism counts, pest dispersal, yield loss, etc. By providing opportunities for post hoc analysis of IPM efficacy, the need for extensive and expensive multi-factorial experiments could be reduced. Growers, however, may not be able to invest the time in recording and reporting suitable data and are probably reluctant to disclose information that is proprietary or sensitive unless they lead to measurable benefits for their operations (Joseph Burman, personal communication, 2015; [122]). Though automated systems that record IPM-relevant data continually may make data collection easier, more standardized and more economical [123, 124], concerns over proprietary data and anonymity are likely to persist as challenges for obtaining big data [125–127].

There are numerous reviews that provide comprehensive, qualitative summaries of experimental data relating to IPM (e.g. [97, 128, 129]). The aim of a meta-analysis is to collate data from published experiments and analyse them quantitatively to increase sample size and thereby determine significant explanatory variables for observed effects [40, 130, 131]. Depending on volume and quality of data, meta-analyses can often reveal trends and patterns that are not easily identified via traditional literature review [132]. For example, a recent meta-analysis of studies on entomopathogenic nematodes across a range of crop types showed that the impact of nematodes on pest populations correlated with improved plant metrics, including yield and biomass [46].

Methods to aid the design of meta-analyses of pest management studies in horticulture have been presented and discussed in the literature [130, 131], but so far, the limited number of meta-analyses for horticultural crops is mostly focused on yield prediction and other plant metrics [132, 133] rather than on pest control. This could be because the availability of suitable studies for inclusion in meta-analyses is limited by their level of detail in reporting statistical treatment effects [131], or because high-quality data from field trials in horticultural research in IPM are often published in non-indexed, specialist publications for practitioners and conference proceedings that are not as easily accessible as research published in international indexed journals [134]. Contributing to this is the underreporting of null results, which may skew meta-analyses [134, 135]. Databases that archive and make available data from growers may therefore serve as

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a new source of data to fuel meta-analyses. More importantly, however, data repositories could support efforts to model and thereby predict the efficacy and sustainability of IPM under various scenarios and at various scales.

Modelling IPM Processes and Outcomes

Mathematical models have been used in a wide range of biological disciplines to move beyond post hoc analyses of experimental and field data via reviews and meta-analyses. A model uses functions and algorithms to generate predictions about future scenarios from a set of starting conditions [77, 136]. In horticulture, models are already widely in use to predict pest population dynamics and forecast the risk of damage to crops (e.g. [137,138]). Models that focus on the responses of pests to control methods used in IPM are less numerous, but can make important predictions about possible outcomes [77]. For example, a predator/pest model created by De Oliveira et al. [139] showed that Neoseiulus californicus (McGregor, 1954), a predatory mite of the two-spotted spider mite, was an effective control for that pest, but that inadvisable release of predators may not be the optimal strategy for control. Chakraborty et al. [140] used a model for predator–prey taxis to show that long-term control of two-spotted spider mite was achievable if predator mortality could be kept low and predator attraction to prey could be improved. Multitrophic models can address some of the complexity of interactions among biological control organisms used in IPM by predicting synergism or interference. Vinatier et al. [141] constructed a tritrophic model for oilseed rape, a pollen beetle pest and its parasitoid on a landscape scale to show that crop rotation and the use of trap crop were more effective as controls than was parasitism. On a landscape scale, models have been used to test the benefits of local and landscape habitat complexity for pest control and to predict the sustainability of agricultural practices [142]. More recently, modelling has also come into focus as a tool for predicting the effect of climate change on crop damage [143]. Models that incorporate climate as a factor can illustrate its influence on outcomes of and interactions between biological control methods. For example, Gebauer et al. [144] used an age-structured simulation model to show that an increase in temperature would not lead to asynchrony between populations of a cabbage aphid pest and their parasitoid, but that wingless aphids may appear earlier in the year, possibly requiring modification of existing pest management. This indicates the value of modelling in future-proofing pest control methods used in IPM. Finally, models can also incorporate economic variables to compare cost and benefit of pest control [77]. For example, models predicting the economic damage threshold for a crop [145] and the likelihood of pest damage exceeding that threshold have already proved invaluable in helping growers identify when to initiate conventional pest control, biological control or other IPM measures [33,146–148] and have helped shape IPM design and policy [149].

Crucially, the value of any model is determined by the quality of data supporting it (‘garbage in, garbage out’). Moreover, models should be validated by testing their predictions against field data [137,150]. This further illustrates the need for rigorous and extensive field trials and collection of ‘big data’ to support the development of models of increasing complexity that can incorporate multiple IPM interactions to predict interference and/or synergies [22]. Finally, crucial to the adoption of models as an element of IPM planning and implementation is their acceptance among consultants and growers [38, 148]. Models and other tools that support decision-making in IPM must therefore not only aim to mirror the true complexity of biological systems, they must also be easy to access and use.

Seeing the Wood for the Trees: the Role of Decision Support Systems (DSS) in IPM

DSS are interactive systems designed to help users make decisions about complex problems, and they have been used in IPM decision-making for over 30 years [122, 151–153]. Initially, DSS were mostly represented by software packages for use on a local personal computer (e.g. [154]), but since the late 1990s, web-based tools and services operated by both public organizations and industry have proliferated [153], each with varying levels of interactivity. The majority of DSS currently available are, however, either specifically designed for or primarily focus on pests and diseases in intensive agricultural crops [38, 122, 155]. A survey conducted by the ENDURE Network in 2007–2008 identified and examined seven DSS for pests on horticultural crops currently in use in Europe, most with potential for integration and/or unification [155]. The Food and Environment Research Agency in the UK is currently leading a collaboration of government and industry partners to survey damage to major agricultural crops and produce forecasts for pest and disease threats that are communicated to growers via the ‘CropMonitor’ website and smartphone application [156]. EPPO is developing a global database to make available all pest information produced by the organization [43]. Though there remains substantial opportunity for further development of DSS in horticulture, there are examples of expansive and sophisticated DSS that are in use. Apple growers in the UK can access the ‘Apple Best Practice Guide’ hosted by the Horticultural Development Company (HDC) to help them identify pests and diseases (pre- and post-harvest) and view information about control methods and IPM programmes suitable for each pest [157]. In the USA, the United States Department of Agriculture (USDA) manages a series of regional IPM
centres that host databases on pests and relevant control methods for use in IPM. In addition, a number of universities involved in IPM research host websites with databases and other online tools for growers, for example North Carolina State University [158]. The University of California Davis hosts a wide-ranging set of resources for agricultural and horticultural crops with pest databases, IPM implementation guides and other information [159].

More recently, DSS have become more interactive and have increased in complexity and scope, integrating database technology with complex models, geographical information systems, knowledge archives and expert networks [38, 153]. They usually incorporate predictive models that can be fed with grower data to produce situation-specific recommendations on IPM [38, 122]. For example, Jones et al. [115] have developed The Washington State University Decision Aid System (DAS) for fruit growers. It currently includes models for ten insect pests and four diseases and automatically collects local weather data to predict pest and disease conditions in the near future (up to 10 days). The system then provides advice on suitable organic and synthetic controls in a database linked to model outputs [115]. Recent surveys indicate that the DAS is valued at US$16 million annually by growers and is used to make management decisions across the majority of the state’s tree fruit production area [160]. The ‘Croprotect’ system currently in development at Rothamsted Research [120] will act as a DSS that integrates databases, user data, GIS data and a curated database of IPM components to produce IPM solutions for users.

While DSS with growing capabilities and greater reach have the potential to further improve decision-making in IPM, they still have some significant limitations as well [38]. A lack of uptake of DSS is a continuing problem as well [122, 152, 161] and ongoing funding is necessary to keep the models and databases that feed DSS up-to-date. Often there are multiple DSS for a given crop or pest – some public, some industry-operated – even at a national level [153, 162]. This creates potential for provision of inconsistent or even contradictory information from different sources, which may complicate rather than simplify decision-making. Bouma [153] notes that the development of multiple national or regional DSS within the same climatic zone and for the same crops and pests is redundant and constitutes a waste of resources. Pests such as D. suzukii have been able to spread across and between continents to cause damage on internationally grown crops [3], but online databases and DSS have not been keeping pace with this international development [153]. Improvements in international collaboration and communication are therefore necessary. Progress is already being made by linking or combining DSS and expanding their use across borders [163] and recent initiatives include funding of projects that aim to innovate and harmonize and/or standardize DSS at regional to transnational levels (ERA-Net ‘Coordinated Integrated Pest Management in Europe’ [164]) and the development of Open-Source DSS platforms that facilitate local adaptation and incorporation of models [165]. Difficulties in achieving sufficient uptake of DSS by growers may also be due to reluctance to adopt new work procedures, implicit differences in how growers and the developers of DSS prioritize outcomes of IPM (e.g. growers are likely to favour reduced pest damage over reduced pesticide treatment and environmental impact) and how they perceive or interpret risk in making IPM decisions [42, 155].

As discussed above, for DSS to accurately model and predict pest damage and IPM outcomes, it is essential that DSS incorporate models predicting interference between IPM components so it can be taken into account in decision-making. For instance, some DSS already help growers minimize the impact of pesticide application on beneficial insects. Beliën et al. [166] have produced a software tool that models earwig populations in orchards and allows growers to choose and time pesticide application such that it minimizes the impact on these beneficial generalist predators. If models like this one can be incorporated into DSS for pest management, it will bring them closer to modelling the full complexity of interactions in IPM. Other ways in which DSS can be expanded is by including (a) decision guides for additional stages in the production process (e.g. preparing fields for crops, storage etc.); (b) tools to evaluate IPM decisions at landscape and local scales; (c) economic models providing cost/benefit analyses of IPM programmes and (d) real-time data input via automated sensors [38, 124]. While DSS will grow increasingly complex along with the knowledge and models that support them, if they are to become more widely adopted by users, this should not result in making user interfaces or outputs more complex [38], especially since adoption of DSS is likely to decrease as complexity increases, even at the expense of accuracy [42]. Rather, the goal should be to develop DSS that cover a geographically and biologically wide range of pests and crops and have highly intuitive user interfaces that allow convenient and mobile access [160]. Moreover, DSS outputs should be easy to interpret and visually intuitive [167] with flexible modes of delivery that can be chosen by users [38]. To increase acceptance of DSS, their accuracy must be confirmed by repeated and rigorous field testing and the end-users must be involved in their design, especially with regards to user-interfaces and output delivery [38, 41, 168]. As Rossi et al. [161] have emphasized, rather than replacing the decision-maker, DSS should aid in decision-making.

Conclusions: IPM: Challenges and Opportunities

Though the scope of knowledge and quality of practice in IPM has dramatically increased in recent years, researchers, industry and growers still find themselves racing to replace synthetic chemical pesticides with robust

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IPM alternatives. There is significant need and scope for improving IPM in each of the four key areas that determine the viability of IPM (efficacy, reliability/ease of use, cost/benefit, sustainability, etc.) and more accurately modelling the complexity of the biological systems in which IPM operates will contribute to achieving this goal. Not surprisingly, this will require significant resources and funding for IPM research and development [22]. By introducing more complexity into IPM theory and practice, however, we create a danger of making practitioners feel increasingly lost in a forest of piecemeal information and insufficiently distinct or persuasive options for pest control using IPM. IPM researchers, industry and – most importantly – consultants and growers must continue to work in close collaboration to move towards a systems view of IPM [5] that takes into consideration ecological complexity [36]. Doing so will inspire necessary innovations in: (i) the design and communication of research; (ii) the collection, management and analysis of ‘big data’ generated by horticultural operations and (iii) the application of knowledge gained through DSS that provide robust, convenient and clear guidance for IPM. We must increase the number of trees in the IPM forest, but not without clearly signposting the wood.

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