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Delivering integrated pest and pollinator management

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Corresponding Author:	Paul Egan Swedish University of Agricultural Sciences Alnarp, SWEDEN
First Author:	Paul A. Egan, PhD
Order of Authors:	Paul A. Egan, PhD
	Lynn V. Dicks, PhD
	Heikki M.T. Hokkanen, PhD
	Johan A. Stenberg, PhD
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Delivering integrated pest and pollinator management

Paul A. Egan^{1,*,@}, Lynn V. Dicks², Heikki M.T. Hokkanen³, Johan A. Stenberg¹

¹ *Department of Plant Protection Biology, Swedish University of Agricultural Sciences, P.O. Box 102, SE-23053 Alnarp, Sweden*

² *Department of Zoology, University of Cambridge, Cambridge, UK; School of Biological Sciences, University of East Anglia, Norwich, UK*

³ *Department of Environmental and Biological Sciences, University of Eastern Finland, Yliopistonranta 1, FIN-70210 Kuopio, Finland*

* Correspondence: paul.egan@slu.se (P.A. Egan)

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Abstract

The need to reduce pollinator exposure to harmful pesticides has led to calls to expedite adoption of integrated pest management (IPM). We make the case that IPM is not explicitly ‘pollinator-friendly’, but rather must be adapted to reduce impacts on pollinators, and to facilitate synergies between crop pollination and pest control practices. To reconcile these diverse management needs, we introduce a systematic framework for ‘integrated pest and pollinator management’ (IPPM). We also highlight novel tools to unify monitoring and economic decision making processes for IPPM, and outline key policy actions and knowledge gaps. We propose that IPPM is needed to promote more coordinated, ecosystem-based strategies for sustainable food production, against the backdrop of increasing pesticide regulation and pollinator dependency in agriculture.

Pests and pollinators matter

In addition to yield loss imposed by insects, weeds, and diseases, over 75 % of the world's major crops are vulnerable to pollination deficit [1], a shortfall in yield owing to suboptimal pollination [2, 3]. **Yield gaps** (see Glossary) may be further widened where pest damage impacts insect pollination, or their management practices interact [4, 5]. Yet despite growing recognition of the need to limit the non-target effects of pesticides on pollinators [6-8], the ways in which pests and pollinators are managed remain largely uncoordinated. It is little appreciated that other pest control practices, including those typically employed in **integrated pest management** (IPM), can also impact pollinators and their ecosystem service to crops. Promoting IPM as a specific response to pollinator decline [9] can as such prove problematic. Similarly, actions taken to manage pollinators have the potential to perpetuate pest problems [10]. But beyond only perpetuating such conflicts, uncoordinated management overlooks opportunities to sustainably reduce inputs and boost yields (e.g., by harnessing complementary or synergetic benefits from pollination and **biological control** services [4, 11]). To therefore address this need for more broadly coordinated ecosystem-based strategies, we introduce here a systematic framework for **integrated pest and pollinator management** (IPPM), together with practical tools for unified decision making and implementation.

Expanding the IPPM concept

IPPM as originally conceptualised by Biddinger and Rajotte [6] is quite narrowly defined; relating specifically to practices aimed at reducing pollinator exposure to conventional pesticides (see 'Conventional pesticides' below). Aside from the use of conventional pesticides, there is a clear need to expand this concept to encompass all elements of the IPM toolbox. IPM has for decades proved instrumental in decelerating yield loss to pests whilst seeking to reduce farmer reliance on agrochemical-based plant protection products [12, 13]. However, although IPM often entails the use of control practices compatible with biological control [14], it does not necessarily follow that effects on pollinators should be neutral. Indeed, as we will see, most IPM actions to combat pests can also affect pollinators, in ways that may be detrimental or beneficial to crop pollination.

Parallel to IPM, recent advances in pollinator management have sought to integrate the various practices used to achieve optimal crop pollination. Different terms and emphases have been applied, including; ‘integrated crop pollination’ [15], ‘integrated pollinator management’ [16], ‘integrated species and habitat management of crop pollination’ [17], and ‘farming with alternative pollinators’ [18]. What unites these concepts is a desire to foster balanced approaches to enhance wild pollinator populations and services whilst minimising reliance on managed pollinators, in particular the Western honey bee (*Apis mellifera* L.). The need to design more comprehensive strategies to manage pollinators, which also incorporates their beneficial and detrimental effects on pest insects, weeds, and diseases, signals a need for more holistic development of the concept of IPPM..

A systematic framework for IPPM

Formally reconciling the goals of IPM and ‘integrated’ crop pollination, together with their respective economic decision making processes, as such is not trivial, and calls for novel conceptual foundations. To this end we propose a systematic framework for integrated pest and pollinator management (Figure 1, Key Figure). Underpinning this framework are practical monitoring and decision support tools developed to help translate the concept of IPPM into action (Box 1, Figure 2).

In the following sections, we present each of the main framework elements of IPPM, including an overview of existing knowledge and research needs. These elements are presented in order of their relative priority in the IPPM hierarchy (Figure 1); starting with actions that generally deliver co-benefits for pest control and pollination, and which are more suited for **preventative** use (i.e., to avoid pest and pollinator **action thresholds** being reached). We then progress to actions that are generally more likely to show conflicts, and which are ideally only used as **curative** measures once action thresholds are already surpassed. We conclude with a focus on combining individual actions to produce coordinated IPPM strategies, and on stimulating uptake of IPPM in policy and practice (Box 2).

Framework elements

Agroecosystem diversity and habitat modification

As a foundational action to prevent pest and pollinator-imposed yield gaps (Figure 1), IPPM promotes the diversification of agroecosystems at crop, field, and landscape levels. In practical terms, this equates to increasing the number of crop and non-crop plants cultivated per unit area and time (see ‘pollinator-friendly cultural control’ below), but in particular to enhancing floral and habitat diversity at local and landscape scales for the attraction and sustenance of beneficial insects.

Floral and habitat diversity are typically promoted in and around crop fields via the maintenance of semi-natural habitat and hedgerows, or by sowing strips/blocks of wildflowers in field margins or directly within the crop. Evidence supports the general benefit of local and landscape diversity for pollinator and natural enemy populations [19-23], despite this often proving context-dependant [24]. However, whilst many guidelines for enhancing local diversity focus on the establishment of flower strips and margins, less attention is afforded to other critical management actions such as their maintenance (e.g., mowing before going to seed) and termination. Insufficient management of even popular floral species, such as buckwheat (*Fagopyron esculentum* Moench), otherwise risks invasive spread [25] and increased use of herbicides. The scale of this problem is, however, likely under-recognised to date, which requires increased attention by researchers and advisors

The benefits of managing local and landscape diversity for pollinators and natural enemies has been demonstrated across diverse crops [26], such as for clover [4] and coffee [11], where complementary or synergistic gains in yield (exceeding the contribution of individual services) can accrue. In practice, managing agroecosystems for better ‘co-delivery’ of services, is still rather constrained by the fact that most studies of pollination and biocontrol functional groups are undertaken in isolation [23]. This tendency therefore limits our understanding of potential additive and interactive effects between pollinators and natural enemies [27], how these groups concurrently respond to local- and landscape-scale diversity [10, 11, 22, 28-31], and in what contexts actions taken to enhance diversity actually translate into increased yield [32].

As a result, crop-specific strategies to manage for multiple service provision still remain scarce [31, 33]. Strategies such as these are however greatly required, given that crop or location-specific demands may frequently call for carefully tailoring floral and habitat composition. This

includes circumstances such as where: (1) certain crop systems or landscapes lack sufficient quantity or quality of resources for pollinators or natural enemies (e.g., forage, nutrition, nesting and shelter sites) [31, 34]; (2) early, late, or mass-blooming crops require phenological complementarity in floral resource availability; (3) visitation by more specialised crop pollinators or natural enemies needs to be encouraged; or (4) existing or introduced floral species themselves pose a weed risk, are weak competitors against agronomic weeds, or co-host specialised pest insects or diseases [35, 36]. Putting in place the above knowledge base for individual crops is therefore a key priority for IPPM, and is needed to guide integrated decision making for multifunctional agroecosystems (see also Box 1).

Pest-resistant and pollinator-attractive cultivars

IPPM encourages the selective use of cultivars showing both high pest resistance and pollinator attractiveness as a preventative measure that is likely to show co-benefits against related yield gaps. The use of resistant cultivars, and the prophylactic induction of host plant defence (i.e., plant vaccination), is hence prioritised within the IPPM framework (Figure 1) as an economically sustainable alternative to the curative use of pesticides. But they are also prioritised because their use can aid against so-called pest-induced pollination deficits [37]. Such deficits emerge due to pollinator avoidance of damaged or infested plants, and appear to be a relatively common ecological phenomenon [38] despite being easily mistaken for pest direct effects on yield. Pest-damaged plants can affect pollinators in different ways; for instance hoverflies, but not honey bees, were found to discriminate against damaged strawberry flowers [5]. Hence given the potential for pest interference with pollination [5], it is therefore important that other IPM strategies, like the use of resistant cultivars, are deployed when seeking to reduce or remove pesticide use.

Potential conflicts between resistance-based pest control and pollination are also important considerations for IPPM. These include, for instance, increased pollinator or natural enemy exposure to defensive compounds in floral rewards [39]; deterrence by induced plant volatiles [37, 40]; untimely initiation of flowering [41]; and reductions in inflorescence size, flower number, and nectar sugar content [42, 43] [44]. The effects of one commonly applied defence elicitor, jasmonate (and its methyl ester), indicate potential impacts on pollinator visitation and

behaviour [37], although such effects are not ubiquitous [42]. Where conflicts do exist, emphasis on non-chemical defences (plant hairs, waxes, etc.) or indirect defence by natural enemies may instead prove useful.

In contrast to extensive efforts to breed for improved crop defences, breeding for improved pollinator attraction remains virtually unexplored [18, 45-47]. Crop cultivars vary widely in their attractiveness to pollinators; with suboptimal pollinator visitation a persistent problem for many [46, 48, 49]. Developing more pollinator-attractive cultivars, in particular harnessing genetic resources offered by crop wild relatives [45], should hence be more widely sought by breeders as a solution to reduce pollination deficits, and to lower the recommended stocking rate (RSRs) of bee colonies for pollination. This is especially true for widespread crops like strawberry (average RSR = 8.6 honey bee colonies/ha) and blueberry (average RSR = 7.5 colonies/ha) [50, 51]. Target traits for breeding could feature the energetic, nutritional, or gustatory properties of nectar and pollen rewards [45, 47, 48]; flower morphology, pigmentation, and scent [47, 52]; and inflorescence architecture [18, 46]. While the extent to which selective breeding may have compromised such functional traits in crops is not known, domestication effects reportedly include loss of floral scent [52] and the alteration of floral reward chemistry with potential consequences for bumble bee disease, nutrition, and gustation [45].

Pollinator-friendly cultural, physical, and mechanical control

Cultural practices bestow numerous co-benefits in cropping systems, which for IPPM can include both pest suppression and enhancement of pollinator habitat and services. But cultural practices can also require careful management of risks, given their potential for disruption [18].

Companion cropping is a cultural practice that perhaps possesses the highest potential to deliver co-benefits for pollination and biocontrol whilst minimising risk of conflict. Companion cropping features the use of crop species or cultivar mixes of all types of spatial arrangement [53] and intended pest suppression function [54, 55]. Predominant practices include intercropping, and the use of trap crops and susceptible cultivars, e.g., to divert insect feeding and oviposition. Indeed while enhanced biocontrol services commonly flow from companion cropping systems [54], where trap crops can provision natural enemies with forage [56] and

nursery sites [57], there has been little examination of how these systems may also affect pollination in terms of potential synergies (i.e., pollinator attraction or pollination facilitation) and conflicts (i.e., pollinator deterrence or pollination competition) [58]. Effective companion systems, from an IPPM perspective, should ideally attract and provision both natural enemies and pollinators whilst still facilitating spill-over of ecosystem services. One potentially important tool to leverage such functionality is flowering phenology [58]; where either maximizing or offsetting companion crop co-flowering could prove beneficial.

Other cultural practices, such as cover cropping, date of sowing, and irrigation, also have the potential to facilitate [59-61] or impede [62, 63] crop pollination and biocontrol services, depending on the context. Here, the use of multi-purpose pollinator-friendly cover crops (e.g., clover and other legumes [18]), dates of sowing that help synchronise crop flowering with peak pollinator availability [63], and methods of irrigation (e.g., which avoid prolonged flooding), can form integral actions within IPPM to balance the needs of pest suppression, resource provision for beneficial insects, and soil and yield enhancement.

The cultural practices carrying the potentially largest risk for conflict are crop rotation and tillage. These practices can negatively affect nesting sites, forage availability, and long-term colonization by wild pollinators [64-66]. The presence and magnitude of these effects, however, can vary by species [67], functional trait (e.g., long- versus short-tongued bees) [66], and nesting behaviour (e.g., in-crop vs. field margin nesters) [60]. By contrast, studies on clover [68] demonstrate the possibility for crop rotation to effectively suppress pests without showing impacts on pollinators and pollination. Although such effects could be strongly modulated by agroecosystem diversity. Likewise, field-scale bee abundance and diversity may even respond positively to alternated tillage (no-till/conventional till rotation), in comparison to no-till alone [67]. Devising more pollinator-friendly ways to implement the above cultural practices, and means to combine these with more foundational IPPM actions (see 'Designing coordinated strategies'), thereby forms a priority area for future research.

Physical and mechanical practices seek to suppress, exclude, or kill pests, but may often require modification in IPPM to avoid negative effects on beneficial organisms. In particular, the expanding use of protective structures and materials in crop production worldwide, including as

a means of physical pest control, signals this area as a priority for development of IPPM strategies. Existing IPPM-type solutions already in practice include the application and removal of netting [69] and floating row covers [70] at critical phenological time points, such that pest suppression benefits can be achieved without compromising pollinator-mediated yield. Bee colonies may alternatively be placed directly into such enclosures for pollination. However, potential risks to their use as such, and in structures such as glasshouses and tunnels, include reduced pollination efficiency and quality of yield [71, 72], as well as increased vectoring of plant diseases such as viruses [73, 74]. Further conflicts may need to be managed between the ability of UV-absorbing screening to suppress pest activity, for instance in whitefly and thrips [75], versus its negative effect on the foraging activity of bees [76] and parasitoids [77].

Mulches are another form of physical control that provide effective means to reduce the field incidence of pest insects, weeds, and diseases. Though their use may necessitate maintenance of bare soil in crops pollinated by ground-nesting bees [78]. The design and use of mulch substrate able to facilitate nesting bees could offer a valuable solution, if viable [79].

Phytosanitary measures, such as the clearance of decaying litter from fields, can likewise provide dual benefits for pest suppression and provision of pollinator habitat, although conflicts can also here arise. For instance, in cocoa agroforestry systems, decaying cocoa pods are known to provision its specialist *Dipteran* pollinator with valuable breeding and larval development sites [80, 81].

Mechanical IPM practices such as insect trapping can provide effective tools against generalist and specialist pests [82]. However, compatible use of these tools in IPPM requires consideration of potential non-target effects on beneficial insects. This is especially true where traps are augmented with scented lures (see 'bioactive natural products'), for instance as part of attract-and-kill strategies. As a whole, the high context-dependency of outcomes for beneficial organisms from physical and mechanical control points to the need for more crop-specific participatory trials of IPPM solutions.

Managed pollinators and biocontrol agents

The IPPM framework affords priority to preventative actions which avoid the need for routine addition of managed pollinators and biocontrol agents in field crops, though less so for

greenhouses, where their use is generally more contained and encouraged. Regardless of location, potential synergies and conflicts between the use of managed pollinators and biocontrol agents deserve attention.

One notable pollination-biocontrol synergy is the ability of certain beneficial insects (so-called ‘double mutualists’) to provide both ecosystem services. Certain hoverfly species represent perhaps the best known example in this regard [31]. Much less obvious is the potential role of other flower-visiting natural enemies as pollinators [83-85], such as parasitoid wasps, non-syrphid *Diptera*, and predatory lacewings and ladybirds. Although many such taxa are generalist, infrequent, and rather ineffective wild pollinators [83], when released in high densities in greenhouses their potential role as double mutualists is not well examined, and could perhaps form a target for future optimisation.

Another prominent synergy is the use of managed bees as ‘flying doctors’ for high-precision application of microbial biocontrol agents to plant-pathogenic hot spots (i.e., flowers). This method, termed entomovectoring [86, 87] or apivectoring, has seen increasing use to combat flower-dependent diseases like grey mould and fire blight, e.g. in strawberry, raspberry, and apple [88]. When functional methods are available, entomovectoring is superior in both efficiency and cost effectiveness in comparison to conventional application [89], and can furthermore improve pollination [87]. Current attempts to adapt this tool for the transfer of insect pathogenic fungi (e.g. against whitefly, *Lygus* bug, and aphids) must seek to better balance the mortality of pests against that of dispensing bees [90], which for bumble bees can be up to 45 % per colony. Future efforts could also seek to optimise the various powder substrates used for entomovectoring, including to reduce any yield-related impacts related to the quantity and germination of pollen dispensed by bees (e.g., due to physical blocking).

Finally, managed pollinators and biocontrol agents can also display antagonistic effects. High-density beekeeping has the potential to negatively impact the abundance and diversity of flower-visiting insects, including both wild pollinators and natural enemies [91, 92], via competition for forage resources and increased exposure to disease. These and other forms of **ecosystem disservice** (e.g. non-selective predation or parasitism by biocontrol agents; pollinator facilitation of weed reproduction) can prove problematic [10, 93]. For instance, Dutka

et al. [93] describe how a commonly used entomopathogenic nematode can cause rapid mortality in foraging *Bombus terrestris* (L.). Arguably not enough attention is afforded to testing and managing the risks that insect and microbial biocontrol agents (including those used in mass release programs) pose to wild pollinators and thereby crop pollination, which is a situation that evidently must change.

Bioactive natural products

The use of natural products showing pest-specific bioactivity is prioritised in IPPM over that of broad-spectrum toxins, regardless of whether these are naturally- or synthetically-derived[94]. Natural products used in pest control include a broad range of substances, including botanical- and microbial-derived metabolites, soaps, insect growth regulators, semiochemicals (e.g., pheromones used for mating disruption), and various possible combinations of the above. In contrast to synthetic pesticides, these substances work to control pests via a more diverse and frequently non-lethal range of mechanisms, such as olfactory and gustatory deterrence, and usually possess shorter environmental persistence times [94].

Despite their growing use in IPM [95], little is known regarding the extent to which natural products could impact pollinators or pollination, though specific cases highlight this possibility. For instance, when used as pest lures, floral volatiles and other plant-derived odours can also risk capturing beneficial insects. This trade-off was demonstrated by Bruce et al. [96], where floral volatiles proved effective in trapping a target pest, but only in addition to large numbers of predatory lacewings and bees (*Apis* and *Halictus* spp.). The use of pest-specific pheromones as lures and mating disruptors [97] offers a promising solution to improve selectively, possibly even for more routine, preventative type use (where costs are not prohibitive), although they are still far from being commonly available for most pest species.

The natural insecticides neem and spinosad provide additional cautionary examples. Low doses of azadirachtin, the most bioactive component of neem, are known to deter honey bees [98, 99], although this effect may [100] or may not [98] actualise in field settings. Spinosad on the other hand can show lethal or sub-lethal toxicity following contact or ingestion, including for honey bees, bumble bees, alkali bees, and alfalfa leafcutter bees [101, 102]. Though such effects are usually absent or less pronounced under typical field application levels (e.g., 120-

480 g/L [102]) and levels found in pollen (0.2-0.8 mg/kg [101]). General risk mitigation measures for toxic or deterrent natural products, as for conventional pesticides, include using only minimum pest-suppressive concentrations (e.g., 30-50 ppm azadirachtin [98]), or limiting application to specific time periods (e.g., for spinosad [102]; in dry conditions post dusk, to limit bee contact with wet residues). More extensive examination of natural product risks (sub-lethal, behavioural, and chronic effects) and mitigation measures will be required as 'biopesticide' use continues to rapidly grow [95].

Conventional pesticides

Informed use of pesticides is accepted within the IPPM framework as a last resort curative action (Figure 1). Its placement as such relates to the role that indiscriminate pesticide use has otherwise played in pollinator decline [103], which in turn can increase costs to remedy pollination deficits [104]. Aside from increased rates of mortality, pesticidal impacts on bees and natural enemies include effects on physiology and behaviour [105], fungicidal impairment of colony initiation and larval development [106, 107], and herbicidal impacts on gut microbiota and floral resource availability at field and landscape scales [103, 108]. Pesticidal impacts are often synergistic [109], in interacting with additional stress factors (e.g., 'the three Ps'; additional pesticides, poor nutrition, and pathogens) [103, 110]. As such, even newly developed substances considered to be 'bee-friendly' can show marked effects when encountered under field-realistic stress scenarios [111]. Growing use of **sentinel hives** [112] offers promise to increase exposure monitoring under realistic conditions, and at landscape scale.

IPPM advocates the use of precautionary actions to limit pollinator and natural enemy exposure to pesticides. Biddinger and Rajotte [6], and additional authors [113, 114], here outline best management practices for pollinators, which include: (1) a shift from prophylactic to risk-informed pesticide use; (2) preferential use of low-risk pesticides that show reduced toxicity or behavioural impacts [114]; (3) restricting spraying to specific times (e.g., non-blooming periods; evening times) when flower foragers are less active; and (4) spraying in appropriate weather conditions to avoid drift and contamination of floral diversity areas [115]. These guidelines also generally hold for protection of natural enemies, and in part for more pollinator-friendly use of herbicides [116].

Designing coordinated strategies

Implementing IPPM entails combining the use of one or more inter-compatible actions for pest and pollinator management, whilst affording priority to those which seek to prevent pest and pollinator-imposed yield gaps in the long run. The design of IPPM strategies will hence involve combining actions in such a way as to facilitate complementary or synergistic benefits for yield, but also to mitigate potential conflicts, e.g., from ecosystem ‘disservices’ [10, 117]. The relative success of a given IPPM strategy may hence be judged by its ability to prevent pest and pollinator densities reaching their action threshold (Figure 2), whilst limiting the need for higher level curative interventions. Here, the use of integrated decision support tools could be of large benefit to stakeholders, in helping to identify strategies affording the highest economic benefit for IPPM (Box 1, Figure 2).

Devising optimal combinations of IPPM actions for crops (or IPPM ‘strategies’) will inevitably require deliberation on compatibility; a property that may be highly crop specific and challenging to foresee in advance of practical trials. Participatory research will in this sense prove critical to advance IPPM (Box 2). Nevertheless, IPPM elements that should combine well together include preventative type actions towards the foundation of the framework in Figure 1, including also cultural practices based on companion cropping. Even in circumstances where preventative actions are not enough to avert regular curative interventions; it may still prove beneficial to combine both types of actions. For instance, action taken to enhance agroecosystem diversity may still help to buffer impacts on pollinators from insecticide use [104] or crop rotation [68]. Similarly, the use of pest-resistant and pollinator-attractive cultivars may still help to reduce the levels of insecticides and managed beneficial organisms needing input.

Concluding remarks

Better integrating the management of pests and pollinators offers stakeholders improved prospects to maximise yield output and stability in ways that reduce external inputs, and balance economic and ecological sustainability needs. As such, IPPM has the potential to address important challenges in agriculture. Not least is the need to meet growing worldwide demand for pollinator-dependant crops [118]. This demand already far surpasses the capacity

of managed honey bees alone to provide pollination [119], and signals that wild pollinators will be increasingly relied upon to ensure food security. At same time legislative restrictions on pesticides are likely to continue to drive IPM adoption [13]; meaning that IPM interference with crop pollination management, and vice versa, may become increasingly apparent unless IPPM-like solutions are applied, including for crops which are not pollinator dependent.

Optimising the use of individual IPPM elements, and trialling means for their integrated application, calls for extensive transdisciplinary research, as posed in the preceding sections, and in 10 key challenges for IPPM (see ‘outstanding questions’). Filling these knowledge gaps on a crop-specific basis, together with cooperative efforts by diverse actors, e.g. to promote monitoring and decision support tools (Box 1) and participatory trials (Box 2), will prove essential to catalyse the adaptation of IPPM.

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Glossary

- **Action thresholds:** are empirically defined densities of pests or pollinators at which action should be taken so as to avoid preventable economic impacts on yield (i.e., yield loss by pests; yield limitation by pollinators).
- **Biological control:** includes pest regulation delivered by wild or augmented natural enemies such as wasps, beetles, predatory mites, and spiders.
- **Ecosystem disservices:** describe natural processes or functions resulting in disfavourable outcomes for human well-being. In context of IPPM, these include e.g., non-target effects by biocontrol agents or pollinator facilitation of weed reproduction, which in-turn feed back to impact farmer profits.
- **Integrated pest management (IPM):** is defined as the application of holistic strategies to manage pests based on the use of compatible methods whilst minimising reliance on conventional pesticides.
- **Integrated pest and pollinator management (IPPM):** is defined as the intersection between IPM and crop pollination management in their widest sense, in which the application of coordinated, ecology-based strategies is prioritised to prevent pest and pollinator-imposed yield gaps.
- **Preventative and curative actions:** refer to those taken to either reduce the opportunity for yield impacts prior to their potential emergence (typically via more long-term, low-risk measures), versus more immediate (and typically more high-risk) actions taken in reaction to a threat.
- **Sentinel hives:** are bee hives which are used to monitor external biological processes via *in situ* sensors or by sampling for external analysis.
- **Yield gaps:** describe the difference between the maximum obtainable yield in a given crop system and that which is observed in the crop, for instance due to yield loss and limitation imposed by pests and pollinators.

Box 1. Unifying monitoring and decision support for IPPM

In putting the framework of IPPM into practice, the questions posed to practitioners can be challenging. Is there a current need to manage pests or pollinators, and which has economic priority? What is the optimal time point for intervention? Is a given action (e.g., insecticide use) likely to produce a net gain after weighing any non-target related costs (e.g., pollinator repellence)?

To address such questions, and to unify economic decision making for IPPM generally, Flöhr et al. [120] introduced a decision metric termed the ‘joint economic impact level’ (EIL) (see also Figure 2). The joint EIL integrates the use of pest economic injury levels [121], as well-established in IPM, with an equivalent derived for pollinators [120]. Context-specific decision support can hence be offered on the basis of which action (managing pests, pollinators, both, or no action) provides the most economically beneficial solution for a given crop, based on current or future prospective needs (Figure 2b). In particular, the joint EIL can account for scenarios where management practices interact (e.g., where companion crops show desirable effects on both weed and natural enemy populations), as well as cases where pests or pollinators exhibit non-linear yield-density relationships.

To facilitate IPPM decision making, field population monitoring is required to render the above metrics actionable. .. As part of this process, the conjoint use of pest and pollinator action thresholds (AT_{pe} and AT_{po}) is therefore recommended [120] (Figure 2a). Establishing empirical pollinator action thresholds for crops, and active monitoring of pollinators as a routine on-farm activity, calls for researchers and stakeholders to adopt new practices and behaviours [120]. Such requirements could therefore pose a barrier to change (Box 2). However, Garret et al [122] demonstrated that UK farmers do appear willing to monitor pollinator numbers, but less so to measure pollination dependence or pollination deficit. This has parallels in IPM, where farmers will measure pest densities, and damage levels, but it is left to researchers to quantify the relationship between the two. Hence when economic benefits can be effectively demonstrated to stakeholders, the value of these metrics and practices for integrative decision making should become much clearer.

Box 2. Stimulating uptake of IPPM in policy and practice

Broadening the well-established framework of IPM to include pollinators and crop pollination (IPPM) requires a change in the way decisions are made in agriculture. This is a substantial challenge. Agriculture is a complex sector, with many different actors, business interests, policy structures, and decision-making processes. Farms and farmers are embedded in 'Agricultural Knowledge and Innovation Systems' (AKIS); connected networks of actors and groups (including government agencies, researchers, extension specialists, and agricultural advisors) who share and act upon emerging knowledge about agricultural practice [123].

To be effective at driving innovation, AKIS require national policy support and coordinating structures such as research networks or centrally funded extension institutions [8]. This combined approach is used in the European Union to promulgate and embed IPM practices, as part of efforts to reduce risks and impacts of pesticides on human health and the environment. Member States of the European Union are obliged to implement the 'general principles' of IPM by the Sustainable Use of Pesticides Directive (Directive 2009/128/EC), through the mechanisms of National Action Plans that encourage the development and introduction of IPM, and mandated advisory services.

In contrast, direct national policy support for pollinators is a more recent phenomenon around the world, usually through national pollinator strategies [9]. These, and other biodiversity-focussed strategies, can offer synergy with policy support for IPM. For instance, both the National Pollinators Strategy for England [124] and the UK's 25 year Environment Plan [125] specify the potential benefits of IPM. This synergy would be enhanced if all these policy documents specified IPPM, defined according to Figure 1.

Many farmers in Europe already take actions to support pollinators, such as managing flower-rich hedgerows and field margins, but seldom explicitly and deliberately do so to support pollinators or crop pollination [126]. Rather, action is motivated in response to agri-environmental policies focused on biodiversity. The IPPM framework can help make the connection between these actions and crop productivity improvements due to pollination. In IPPM, there will be a need to shift emphasis away from the use of both conventional pesticides and managed pollinators to the more ecology-based strategies at the base of Figure 1. Here particularly, direct practical demonstration is key to encouraging farmers and advisers

to take up new practices or concepts. For example, farmer fields schools in many developing countries have been demonstrated to be effective in leading to uptake of IPM practices [127]. We also suggest developing and delivering educational curricula and training on IPPM, in particular targeting farmers, advisors, and extension educators whom already train others in IPM, but generally lack a firm grounding in pollinator biology and pollination. Finally, decision support tools, as discussed in Box 1, are only likely to enhance uptake of IPPM if they are developed in partnership with users, taking into account important factors such as usability, cost-effectiveness, performance, relevance, and compatibility with compliance demands [128].

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Figure legends

Figure 1. Systematic framework for integrated pest and pollinator management (IPPM). The framework of IPPM seeks to balance the management of pest insects, weeds, and diseases with that of pollinators and crop pollination. The placement of actions within the IPPM hierarchy is based firstly on their potential to facilitate co-benefits for pollination and pest control, alone or when used in combination with other actions, relative to their potential to show conflicts; and secondly in relation to whether they are usually applied in a manner to prevent action thresholds being surpassed (e.g., habitat modification to promote wild beneficial organisms), rather than in a curative manner (e.g., the application of managed beneficial organisms) once this has already happened. As such, foundational actions in the IPPM framework (darker colours) provide a generally more favourable basis for the long-term prevention of pest and pollinator-imposed yield gaps, as compared to lower priority actions towards the tip (lighter colours) which ideally should receive more sparing use.

Figure 2. Practical approaches to unify decision making for integrated pest and pollinator management (IPPM). **Panel A** highlights the use of novel monitoring and economic decision support metrics for pollinator management, i.e., the pollinator EIL ('economic impact level') and pollinator action threshold [120]; developed as counterparts to the pest EIL ('economic injury level') and pest action threshold used in IPM. These metrics provide an economic basis to unify what are otherwise disparate impacts on yield (i.e., yield loss due to pest damage; yield limitation due to pollination deficit), and to thereby integrate the decision-making goals underlying IPM and pollinator management. Collectively, the pest and pollinator EIL hence describe the maximum pest density, and minimum pollinator density, that must be tolerated in a crop before action becomes economically justified (i.e., where economic gain g exceeds cost of action). In practice, action should usually be taken before these densities are reached, i.e., once established action thresholds for pests (AT_{pe}) or pollinators (AT_{po}) are surpassed. Depicted are pest and pollinator densities in a scenario where timely action is either taken (black solid lines) or not (grey dashed lines); in which case economic impacts on yield are incurred. One drawback to the pest and pollinator EIL is that they are independent metrics, and cannot account for interactive effects (e.g., management synergies or conflicts), which are of large

potential importance for IPPM. **Panel B** therefore highlights how these metrics can be integrated in the form of a joint EIL ('joint economic impact level') [120]. The joint EIL works by adjusting the pest and pollinator density at which an action becomes economically justified after accounting for any extra costs or benefits from interactive effects. For example, the pest density at which a control action (e.g., insecticide use) is triggered may therefore increase in proportion to the extent it might also decrease pollinator density.. Depicted is a typical 'decision landscape' for a crop, following parameterisation in the joint EIL tool (see [120]). Managing both pests and pollinators is recommended here as the most beneficial action, which, under the hypothetical management scenarios parameterised, should return densities to levels that no longer require action.

Figure 2

[Click here to access/download;Figure;Figure_2.jpg](#)