Integrated pest and pollinator management – expanding the concept

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The objective of integrated pest and pollinator management (IPPM) is to co-manage for pest control and pollination goals. Departing from the well-established concept of integrated pest management, we include pollinator management in a hierarchical decision support system of management actions. We depict this support system as an IPPM pyramid. Priority is given to proactive measures at the base of the pyramid, which are undertaken through landscape and crop field management of mobile organisms, primarily arthropods. Farther up the pyramid, practices in the form of reactive use of biotic and abiotic inputs should align with basal actions. The goal of IPPM is to minimize trade-offs, and to maximize co-benefits and synergies between pest and pollinator management. We contend that IPPM has the potential to contribute to sustainable pest control and crop pollination, as well as provide broader environmental benefits.

In a nutshell:

• There are numerous reasons to co-manage for pest control and pollination based on the often overlapping ecology of pests, natural enemies, and pollinators, and their non-independent effects on crop yield
• Integrated pest and pollinator management (IPPM) is a framework that can be used to co-manage for ecosystem functions driven by pests, natural enemies, and pollinators
• The IPPM pyramid represents a hierarchical decision support system that prioritizes base-level, proactive actions over apex, reactive actions to achieve both pest and pollinator management goals
• Strategies for simultaneously managing for pest control and pollination goals through IPPM are presented

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actions at the top, which are implemented only if proactive actions are insufficient for managing pests or keeping damage below defined thresholds. A parallel hierarchical decision structure can be used for managing pollination, where pest and pollinator co-management form an IPPM pyramid (Figure 2; see also Egan et al. 2020). Actions at the base of the IPPM pyramid make greater use of ecological processes (eg ecosystem services delivered by natural enemies and pollinators; Dainese et al. 2019) or of the structure and design of managed and natural elements of landscapes that directly suppress pests (Gurr et al. 2017). Actions at the top replace biodiversity-based practices with synthetic management alternatives, such as pesticides. In the following sections, we review pest and pollinator management practices and highlight potential IPPM synergies, co-benefits, or trade-offs at each level of the pyramid. A summary of the evidence for effects of actions on pests, natural enemies, and pollinators at each level of the pyramid is presented in Table 1.

**Landscape management**

Pest management at the bottom of the IPPM pyramid targets actions at the landscape scale that directly suppress pests and support diverse and abundant communities of natural enemies that promote biodiversity-based pest control (Gurr et al. 2017). Similarly, landscape-scale actions can support pollinators and pollination services (Isaacs et al. 2017). Protecting or restoring natural or semi-natural habitat, increasing the diversity of both wild and crop plants, and ensuring resource continuity for natural enemies and pollinators forms the base of the IPPM pyramid.

Abundance of semi-natural habitat within the landscape can in some cases benefit natural enemies and pest control (Chaplin-Kramer et al. 2011; Rusch et al. 2016). However, responses among natural enemies differ depending on the type of semi-natural habitat; moreover, pests can also benefit from semi-natural habitat, resulting in variable outcomes for pest control (Karp et al. 2018). Semi-natural habitats in agricultural lands tend to benefit pollinators more consistently (Kennedy et al. 2013). The more idiosyncratic response of pest control might be due to the higher tri-trophic complexity (eg Snyder and Wise 2001) and taxonomic diversity of functionally important organisms involved in determining pest control versus pollination outcomes (Karp et al. 2018).

Crop type and diversity along with landscape configuration affect pest and pollinator management. Reducing the spatio-temporal continuity of a host crop could effectively reduce pest abundance, particularly of host-specialized pests (Figure 3; Root 1973; Delaune et al. 2019), whereas increased crop diversity benefits biological pest control by naturally occurring predators (Redlich et al. 2018). The effects of crop diversity on pollinators may be more complex and depend on crop identities and management intensity, where mass-flowering crops (but not intensively managed cereals) promote pollinator populations (Figure 3; Rundlöf et al. 2014; Hass et al. 2018).

(Figure 1; Tamburini et al. 2019). More specifically, pollination benefits are often enhanced under effective pest control, and this appears to be especially true for pest damage to reproductive structures of crop plants (Tamburini et al. 2019). For this reason, the potential economic gains of enhancing crop yield that result from either pest or pollinator management are not determined independently. IPPM approaches take this non-independence into account and harness the synergistic opportunities presented by effective co-management. Crop yield is impacted by both pest damage and pollination, and provides a common currency for uniting the two processes (Figure 1; Saunders et al. 2016). Conducting yield-based analyses allows consideration of net benefits or costs by quantifying the marginal gains or losses of various strategies and actions that support pest control and pollination or increase one at the expense of the other.

**The IPPM pyramid**

A comprehensive IPM program is commonly depicted in the form of a pyramid (eg Hokkanen 2015). The pyramid shape illustrates a tiered decision support system, with priority given to proactive actions at the base and reactive
Achieving IPPM co-benefits may therefore require more nuanced selection of crop composition rather than simply increasing crop diversity. Landscape configurations in the form of landscapes with small and irregularly shaped fields and patches of semi-natural habitat benefit both pollination and pest control (Martin et al. 2019).

Advancing IPPM at the landscape scale will require a deeper understanding of the ecology of pests, natural enemies, and pollinators. The goal at the landscape scale should be to ensure resource continuity for pollinators and natural enemies while decoupling resources for pests. Taking advantage of differences in mobility among organism groups might render co-management opportunities by ensuring resource continuity in time and space at scales suitable for beneficial arthropods but not for species that damage crops (Figure 3; Thies et al. 2005). Another opportunity is to take advantage of differences in host-plant and habitat preferences between pests and pollinators, for instance by substituting host crop cover with alternative non-host plants to disrupt resource continuity for pests while ensuring that substituted crops provide resources for pollinators and natural enemies (Schellhorn et al. 2015; Delaune et al. 2019). At the landscape scale, this can be achieved for multiple crops that benefit from generalist pollinators and natural enemies but suffer primarily from specialized pests.

### Crop field management

A wide variety of field-based actions have been developed to prevent pest outbreaks, collectively referred to as "cultural control" approaches (Bajwa and Kogan 2004). Cultural control includes such actions as increasing within-field plant diversity, planting pest-resistant cultivars, and modifying soil tillage and agronomic inputs like fertilization and irrigation. For several of these practices, impacts on pollinators are poorly understood and considerable research is needed before IPPM can be implemented successfully.

Plant diversity can be increased in the cropped field or along its borders to promote pest control, through both bottom-up and top-down paths (Root 1973); examples include intercropping (Iversen et al. 2014); cover cropping (Schipanski et al. 2014); addition of non-cropped vegetation, such as flower strips or hedgerows (Tschumi et al. 2015; Morandin et al. 2016); and reducing weed control (DiTommaso et al. 2016). Flower strips and hedgerows (Blaauw and Isaacs 2014; Morandin et al. 2016) and reduced weed control (DiTommaso et al. 2016) can also promote pollinators and crop pollination.

Although the effects of intercropping and cover cropping on pollinators are less well understood, these approaches show promise when the cropping system is diversified through the addition of flowering herbs (Mallinger et al. 2019). Cropping systems containing greater plant diversity have often been developed separately for pest control and pollination. Careful selection of plants characterized for their effects on pests, natural enemies, and pollinators (Lundin et al. 2019), as well as

| Table 1. Summary of effects of actions across the levels of the integrated pest and pollinator management pyramid on pests, natural enemies, and pollinators |
|---------------------------------------------------------------|
| **Pests** | **Natural enemies** | **Pollinators** |
| Artificial pollination | ↔ | ↔ | ↔ |
| Pesticide use | ↓ | ↓ | ↓ |
| Biocontrol agents | ↓ | ↑ | ↔ |
| Managed pollinators | ↔ | ↔ | ↑ |
| Irrigation | ↑↑ | ↓ | ↑ |
| Organic fertilizer | ↓ | ↑ | ↔ |
| Flower strips | ↑↑ | ↑ | ↔ |
| Crop diversity | ↓ | ↑ | ↔ |
| Semi-natural habitat | ↑↑ | ↓ | ↑ |

Notes: upward pointing arrows = positive effects; downward pointing arrows = negative effects; sideways arrows = neutral effects. Upward and downward pointing arrows in the same cell indicate both positive and negative effects. Arrows represent generalizations and should not be interpreted as universally true (see also Panel 1).
their weediness, would allow for diversification strategies that support natural enemies and pollinators without benefitting crop pests or exacerbating weed-associated problems. Improving our general understanding of resource use of functionally important arthropods is needed to fully capture the potential of plant diversification at the field scale as an IPPM tool.

Using crop cultivars that are resistant to pests is an essential tool for pest management (Stenberg 2017). For pollinator management, a similar strategy is to breed for or select cultivars that are attractive to pollinators. A key challenge for breeding and cultivar selection from an IPPM perspective would be the simultaneous mapping and consideration of multiple crop traits, including pest resistance, pollinator dependency and attraction, and crop yield.

Pest management for crops also entails modification of agronomic inputs, such as fertilizer and water. For example, organic fertilizers can improve top-down pest control via beneficial effects on predators and bottom-up control by enhancing crop defense against pests (Rowen et al. 2019) while at the same time increasing crop flower visitation by pollinators (Banaszak-Cibicka et al. 2019). Effects of water availability on pests, natural enemies, and pollinators are generally not well known. Irrigation, especially by flooding, can disturb predators (Baraibar et al. 2009), whereas water availability can have both positive and negative effects on crop pests and pest damage to crops (Daane and Williams 2003). Managing for adequate soil moisture and avoiding both under- and over-irrigation can benefit pollinator crop visitation through increased nectar production (Gillespie et al. 2015).

In addition to cultural control techniques, other approaches, such as physical control of insect pests (e.g., exclusion netting and row covers), have received greater attention in recent years, many of which can require integration with pollinators when the crop is pollinator dependent (Minter and Bessin 2014; Leach et al. 2016).

The effectiveness of IPPM practices at the field scale (e.g., addition of flower strips) on pollination and pest control depends on the landscape context, with some evidence that benefits are greater in simple than in complex or cleared landscapes (Jonsson et al. 2015; Grab et al. 2018). Field and landscape management actions sometimes overlap, as field actions employed over large areas scale-up to become landscape-level practices.

### Sampling, monitoring, and thresholds

Monitoring and sampling are fundamental components of pest management that are used, along with thresholds, to determine control actions. The economic threshold (ET) defines the lowest pest density for which action must be taken to avoid reaching the economic injury level (EIL), which is the lowest pest density that incurs financial loss as a result of crop injury that exceeds the cost of the control action (Stern et al. 1959). In practice, however, ETs for specific pests and cropping systems are often unavailable, outdated, or lack scientific support, possibly due to the extensive amount of data needed for their determination. In contrast, the goal of pollination management is to maintain pollinator populations above a certain threshold such that economic losses due to insufficient pollination are avoided, necessitating the development of a pollinator economic impact level (PEIL) analogous to the EIL (Flöhr et al. 2020). The PEIL is a potentially useful metric to determine whether pollinator management actions are justified, but as with EILs, quantification of crop-specific PEILs requires substantial amounts of ecological and economic data. Specifically, more comprehensive knowledge of how
to rapidly determine whether crops are pollen limited using field sampling data (but see Garibaldi et al. 2020) would be needed to increase the usefulness of the PEIL concept. In addition, although several pest management actions (eg pesticide application) can be performed quickly, management actions for pollinators may be logarithmically challenging to implement rapidly in response to monitoring (eg the ability to add managed bees may depend on the availability of surplus hives). EIL and PEIL can also be merged into a single decision metric – the joint economic impact level (jEIL) – that integrates crop yield limitation attributable to the actions and availability of both pests and pollinators (Flöhr et al. 2020).

### Biotic inputs

Reared and released biological control agents, primarily consisting of invertebrates and microorganisms, are often used as biotic inputs for pest management. Historically, exotic biological control agents were typically introduced with the goal of achieving long-term pest control (ie classical biological control), but augmentative releases to strengthen existing natural enemy populations in the field (ie augmentative biological control) is becoming an increasingly common strategy (van Lenteren et al. 2018).

Managed bees are ubiquitous biotic inputs for crop pollination. As with biological control agents, bees are used to augment naturally occurring, service-providing organisms. Globally, the European honeybee (*Apis mellifera*) is the dominant managed crop pollinator, while several bumblebee (*Bombus* spp) and solitary bee species are also regionally employed (Isaacs et al. 2017). The contribution of managed honeybees to yield varies greatly among crops and regions (Garibaldi et al. 2013). Future research is needed to explore the potential of using species other than honeybees for crop pollination and to determine suitable stocking densities of managed pollinators (Isaacs et al. 2017).

Pest management and pollinator management that both rely on biotic inputs operate largely independently from each other. One important exception is the entomovectoring technique, whereby insects (typically bees) serve as vectors to deliver microbial control agents against pathogens and insect pests (Mommaerts and Smagghe 2011). There is a potential for synergy between actions aiming to create landscapes and fields with robust populations of wild beneficial arthropods and using biotic inputs for pest and pollinator management. Released biological control agents benefit from complex, resource-rich landscapes (Perez-Alvarez et al. 2019); likewise, landscapes with diverse floral resources benefit managed pollinators (Smart et al. 2016). Conversely, releasing biotic IPPM agents into resource-poor landscapes may lead to increased competition between wild and managed pollinators (Herbertsson et al. 2016) or antagonistic interactions between naturally occurring and introduced natural enemies (Perez-Alvarez et al. 2019).

### Abiotic inputs

Despite 60 years of IPM development, chemical pest control remains the standard method of pest management in intensive agricultural systems throughout much of the world (Zalucki et al. 2009; Hokkanen 2015). In Europe and North America, insecticide use patterns have changed over time, with lower quantities but more potent insecticides being applied (Douglas et al. 2020).

Analogous to the fully synthetic inputs in the form of pesticides used for controlling pests, several methods for artificial pollination (eg hand pollination, pollen spraying, other mechanical devices) are used for pollen transfer (Westerkamp and Gottsberger 2000; Potts et al. 2018). However, use of artificial pollination techniques has yet to reach the same level of ubiquity as that of chemical pesticides, and such techniques are unlikely to serve as substitutes for bees or other pollinators on a large scale. However, artificial pollination techniques could play a niche role for crops grown in settings where managing for pollinators in sufficient numbers is not possible (Potts et al. 2018).

The overlapping physiologies, activity patterns, and habitats of pests, natural enemies, and pollinators underscore how the use of insecticides may be potentially disruptive for IPPM co-benefits. Insecticide use for pest control is linked with risks for trade-offs both in terms of negative effects on natural enemies and pollinators (Figure 4; Bommarco et al. 2011; Rundlöf et al. 2015). Indiscriminate insecticide application can lead to negative effects on biological control that are greater than the targeted effect on the pest (Bommarco et al. 2011), and can also detrimentally affect pollinators (Rundlöf et al. 2015), which in turn can have negative repercussions for crop yield (Stanley et al. 2015). On the other hand, use of low-risk insecticides on flowering crops may also benefit bees by protecting their food resources from pest damage (Rundlöf and Lundin 2019).

It is unclear how the landscape context moderates negative effects of pesticides on natural enemies and pollinators. A complex and resource-rich landscape can buffer for negative effects of pesticides on pollinators (Park et al. 2015), but pesticides can also negate positive effects of landscape complexity on biological control (Ricci et al. 2019). Research on how pesticides affect both pest control and pollination, and how these functions in turn affect yield, is urgently needed to calibrate pesticide use to levels that maximize farmers’ economic returns while reducing the risk of adverse impacts on ecosystem functioning (Catarino et al. 2019). An integral part of IPPM is to reduce insecticide use by exploring effects on pests and pollinators of alternative control methods from more basal parts of the IPPM pyramid (Figure 4), or evaluating alternative abiotic inputs such as biotechnological options (eg RNA interference; Zotti et al. 2018). Research and innovation that contribute to insecticide applications targeting pests over natural enemies and pollinators are also central to IPPM development (Biddinger and Rajotte 2015), and this could be achieved by applying pesticides at
times (eg pre-flowering) and locations within the crop where pest activity is high relative to beneficial arthropod activity.

### Advancing IPPM in practice

Within our IPPM framework (Figure 2), current common practice essentially takes the form of an inverted pyramid, with pesticide use and a single managed pollinator species (*A mellifera*) dominating pest and pollinator management, respectively. Although recognition of the need to integrate pest control and pollination has grown, the inverted perspective has been largely retained through consideration of adaptive pesticide use to minimize risks to a single pollinator species (ie *A mellifera*; Biddinger and Rajotte 2015; Curtis et al. 2019). However, dwindling options for chemical pest control and increasing pressure on honeybee health will likely necessitate more diversified strategies in the future. Important research priorities to further advance the development of IPPM are listed in Panel 1.

Public and private crop advisors, pest control specialists, and educators play important roles in linking pest management research with practice (Lamichhane et al. 2016). To develop IPPM in practice, we believe that the focus of agriculture extension services must be expanded to take into account pollinator management based on the IPPM framework. Likewise, advancing IPPM in practice would benefit from pest management being considered in services provided by apiculture extension officers and experts in pollinator conservation (Sponsler et al. 2019). An important first step toward facilitating IPPM adoption would be the development of guidelines for the practical implementation of elements within the holistic IPPM framework (Figure 2). Shifting practice from an inverted to an upright model will require formulation of clear guiding principles, well-designed messaging, and a delivery system for advisors and practitioners. Because specific IPPM goals will vary among regions, farming systems, and practitioners, adoption of IPPM will require tiered practices that allow flexibility in employing alternative or selected parts, backed by clear economic validation that also recognizes risk and uncertainty of practices.

One potential complicating factor for implementation of IPPM at the landscape scale is that pests, natural enemies, and pollinators are generally affected by management practices beyond the scale of the individual field or farm (the typical management unit for these organisms). This can create a spatial mismatch whereby benefits deriving from IPPM management at the field or farm level accrue beyond the management unit. Furthermore, agri-environmental policies typically target individual fields or habitats, such that policy instruments facilitating efficient management of agricultural landscapes are often lacking (Goldman et al. 2007). A combination of policy development and voluntary engagement of communities of land managers (Goldman et al. 2007; Brewer and Goodell 2012) holds promise to advance landscape-scale IPPM. Such

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### Panel 1. Research priorities for integrating pest and pollinator management

- Developing a deeper understanding of the ecology (especially movement ecology) of pests, natural enemies, and pollinators in agricultural landscapes.
- Developing a stronger evidence base for biodiversity-based landscape and field management actions at the base of the integrated pest and pollinator management (IPPM) pyramid (Figure 2), focusing particularly on the actions’ potential to contribute to crop yield and economic profit.
- Exploring how pesticide use can be incorporated into IPPM in ways that are highly effective in controlling pests but that have minimal effects on pollinators and natural enemies.
- Developing and evaluating IPPM strategies that incorporate multiple management actions targeting both crop pests and pollinators.
policy instruments and partnerships could enable coordination of local interventions among farmers or contribute to landscape-scale crop rotations that favor pollinators and natural enemies over pests (Figure 3).

Conclusions

We present here a framework for expanding IPM to include pollinator management, resulting in IPPM. This approach creates opportunities for increasing synergies while limiting trade-offs of proactive actions to simultaneously achieve pest control and pollination goals through largely biodiversity-based landscape and field management actions at the base of the IPPM pyramid. Several field and landscape management actions within IPPM are likely to enhance additional ecosystem services, such as those delivered by belowground biotic communities, making it possible to align IPPM with the wider concept of ecological intensification (Kleijn et al. 2019). Proactive IPPM would also enhance environmental benefits by reducing input use and increasing biodiversity. In conclusion, implementing an expanded IPPM concept will contribute to sustainable pest control and crop polli- nation by capitalizing on co-management potentials.

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References

Bajwa WI and Kogan M. 2004. Cultural practices: springboard to IPM. In: Koul O, Dhaliwal GS, and Cuperus GW (Eds). Integrated pest management: potential, constraints and challenges. Wallingford, UK: CABI Publishing.

Banaszak-Cibicka W, Takacs V, Kesy M, et al. 2019. Manure application improves both bumblebee flower visitation and crop yield in intensive farmland. Basic Appl Ecol 36: 26–33.

Baraibar B, Westerman PR, Carrión E, and Recasens J. 2009. Effects of tillage and irrigation in cereal fields on weed seed removal by seed predators. J Appl Ecol 46: 380–87.

Biddinger DJ and Rajotte EG. 2015. Integrated pest and pollinator management – adding a new dimension to an accepted paradigm. Curr Opin Insect Sci 10: 204–09.

Blauw BR and Isaacs R. 2014. Flower plantings increase wild bee abundance and the pollination services provided to a pollination-dependent crop. J Appl Ecol 51: 890–98.

Bommarco R, Miranda F, Bylund H, and Björkman C. 2011. Insecticides suppress natural enemies and increase pest damage in cabbage. J Econ Entomol 104: 782–91.

Brewer MJ and Goodell PB. 2012. Approaches and incentives to implement integrated pest management that addresses regional and environmental issues. Annu Rev Entomol 57: 41–59.

Catarino R, Bretagnolle V, Perrot T, et al. 2019. Bee pollination outperforms pesticides for oilseed crop production and profitability. P Roy Soc B-Biol Sci 286: 20191550.

Chaplin-Kramer R, O’Rourke ME, Blitzer EJ, and Kremen C. 2011. A meta-analysis of crop pest and natural enemy response to landscape complexity. Ecol Lett 14: 922–32.

Curtis R, Ludwig G, Steeger T, et al. 2019. Honey bee best management practices for California almonds. Modesto, CA: Almond Board of California.

Daane KM and Williams LE. 2003. Manipulating vineyard irrigation amounts to reduce insect pest damage. Ecol Appl 13: 1650–66.

Dainese M, Martin EA, Aizen M, et al. 2019. A global synthesis reveals biodiversity-mediated benefits for crop production. Science Advances 5: eaax0121.

Delaune T, Ballot R, and Sausse C, et al. 2019. Higher surfaces of a crop in the landscape increase outbreak risks the following growing season. bioRxiv; doi.org/10.1101/641555.

DiTommaso A, Averill KM, Hoffmann MP, et al. 2016. Integrating insect, resistance, and floral resource management in weed control decision-making. Weed Sci 64: 743–56.

Douglas MR, Sponsler DB, Lonsdorf EV, and Grozinger CM. 2020. County-level analysis reveals a rapidly shifting landscape of insecticide hazard to honey bees (Apis mellifera) on US farmland. Sci Rep-UK 10: 797.

Egan PA, Dicks LV, Hokkanen HM, and Stenberg JA. 2020. Delivering integrated pest and pollinator management (IPPM). Trends Plant Sci 25: 577–89.

Flöhr A, Stenberg JA, and Egan PA. 2020. The joint economic impact level (jEIL): a decision metric for integrated pest and pollinator management. In: Gao Y, Hokkanen H, and Menzler-Hokkanen I (Eds). Integrative biological control: ecostacking for enhanced ecosystem services. Dordrecht, the Netherlands: Springer.

Garibaldi LA, Sáez A, Aizen MA, et al. 2020. Crop pollination management needs flower-visitor monitoring and target values. J Appl Ecol 57: 664–70.

Garibaldi LA, Steffan-Dewenter I, Winfree R, et al. 2013. Wild pollinators enhance fruit set of crops regardless of honey bee abundance. Science 339: 1608–11.

Gillespie S, Long R, and Williams N. 2015. Indirect effects of field management on pollination service and seed set in hybrid onion seed production. J Econ Entomol 108: 20181102.

Goldman RL, Thompson BH, and Daily GC. 2007. Institutional incentives for managing the landscape: inducing cooperation for the production of ecosystem services. Ecol Econ 64: 333–43.

Grab H, Poveda K, Danforth B, and Loeb G. 2018. Landscape context shifts the balance of costs and benefits from wildflower borders on multiple ecosystem services. P Roy Soc B-Biol Sci 285: 20181102.

Gurr GM, Watten SD, Landis DA, and You M. 2017. Habitat management to suppress pest populations: progress and prospects. Annu Rev Entomol 62: 91–109.

Hass AL, Kormann UG, Tscharrntke T, et al. 2018. Landscape configurational heterogeneity by small-scale agriculture, not crop
diversity, maintains pollinators and plant reproduction in western Europe. *P Roy Soc B-Biol Sci* **285**: 20172242.

Herbertsson L, Lindström SAM, Rundlöf M, et al. 2016. Competition between managed honeybees and wild bumblebees depends on landscape context. *Basic Appl Ecol* **17**: 609–16.

Hokkanen HM. 2015. Integrated pest management at the crossroads: science, politics, or business (as usual)? *Arthropod-Plant Inte* **6**: 543–45.

Isaacs R, Williams N, Ellis J, et al. 2017. Integrated crop pollination: combining strategies to ensure stable and sustainable yields of pollination-dependent crops. *Basic Applied Ecol* **22**: 44–60.

Iverson AL, Marín LE, Ennis KK, et al. 2014. Do polycultures promote win–wins or trade-offs in agricultural ecosystem services? A meta-analysis. *J Appl Ecol* **51**: 1593–602.

Jonsson M, Straub CS, Didham RK, et al. 2015. Experimental evidence that the effectiveness of conservation biological control depends on landscape complexity. *J Appl Ecol* **52**: 1274–82.

Karp DS, Chaplin-Kramer R, Meehan TD, Jonsson M, Straub CS, Didham RK, et al. Lundin O, Ward KL, and Williams NM. 2019. Identifying native pollinators and plants for coordinated habitat management of arthropod pollinators, herbivores and natural enemies. *J Appl Ecol* **56**: 655–76.

Lundin O, Ward KL, and Williams NM. 2019. Identifying native plants for coordinated habitat management of arthropod pollinators, herbivores and natural enemies. *J Appl Ecol* **56**: 311–23.

Lundin O. 2019. No-till protects spring oilseed rape (*Brassica napus* L) against crop damage by flea beetles (*Phyllotreta spp*). *Agr Ecosyst Environ* **278**: 1–5.

Lundin O, Rundlöf M, Smith HG, and Bommarco R. 2016. Historical change and drivers of insect pest abundances in red clover seed production. *Agr Ecosyst Environ* **233**: 318–24.

Mallinger RE, Franco JG, Prischmann-Voldseth DA, and Prasifka JR. 2019. Annual cover crops for managed and wild bees: optimal plant mixtures depend on pollinator enhancement goals. *Agr Ecosyst Environ* **273**: 107–16.

Martin EA, Dainese M, Clough Y, et al. 2019. The interplay of landscape composition and configuration: new pathways to manage functional biodiversity and agroecosystem services across Europe. *Ecol Lett* **22**: 1083–94.

Minter LM and Bessin RT. 2014. Evaluation of native bees as pollinators of cucurbit crops under floating row covers. *Environ Entomol* **43**: 1354–63.

Mommaerts V and Smagghe G. 2011. Entomovectorying in plant protection. *Arthropod-Plant Inte* **5**: 81–95.

Morandin LA, Long RF, and Kremen C. 2016. Pest control and pollination cost–benefit analysis of hedgerow restoration in a simplified agricultural landscape. *J Econ Entomol* **109**: 1020–27.

Oerke EC. 2006. Crop losses to pests. *J Agr Sci* **144**: 31–43.

Park MG, Blitzer EJ, Gibbs J, et al. 2015. Negative effects of pesticides on wild bee communities can be buffered by landscape context. *P Roy Soc B-Biol Sci* **282**: 20150299.

Perez-Alvarez R, Nault BA, and Poveda K. 2019. Effectiveness of augmentative biological control depends on landscape context. *Sci Rep-UK* 9: 8664.

Potts SG, Neumann P, Vaissière B, and Veecklen NJ. 2018. Robotic bees for crop pollination: why drones cannot replace biodiversity. *Sci Total Environ* **642**: 665–67.

Redlich S, Martin EA, and Steffan-Dewenter I. 2018. Landscape-level crop diversity benefits biological pest control. *J Appl Ecol* **55**: 2419–28.

Ricci B, Lavigne C, Alignier A, et al. 2019. Local pesticide use intensity conditions landscape effects on biological pest control. *P Roy Soc B-Biol Sci* **286**: 20182898.

Root RB. 1973. Organization of a plant–arthropod association in simple and diverse habitats: the fauna of collards (*Brassica oleracea*). *Ecol Monogr* **43**: 95–124.

Rowen E, Tooker J, and Blubaugh C. 2019. Managing fertility with animal waste to promote arthropod pest suppression. *Biol Control* **134**: 130–40.

Rundlöf M and Lundin O. 2019. Can costs of pesticide exposure for bumblebees be balanced by benefits from a mass-flowering crop? *Environ Sci Technol* **53**: 14144–51.

Rundlöf M, Persson AS, Smith HG, and Bommarco R. 2014. Late-season mass-flowering red clover increases bumble bee queen and male densities. *Biol Conserv* **172**: 138–45.

Rundlöf M, Andersson GK, Bommarco R, et al. 2015. Seed coating with a neonicotinoid insecticide negatively affects wild bees. *Nature* **521**: 77–80.

Rusch A, Chaplin-Kramer R, Gardiner MM, et al. 2016. Agricultural landscape simplification reduces natural pest control: a quantitative synthesis. *Agr Ecosyst Environ* **221**: 198–204.

Saunders ME, Peisley RK, Rader R, and Luck GW. 2016. Pollinators, pests, and predators: recognizing ecological trade-offs in agroecosystems. *Ambio* **45**: 4–14.

Schellhorn NA, Gagic V, and Bommarco R. 2015. Time will tell: resource continuity bolsters ecosystem services. *Trends Ecol Evol* **30**: 524–30.

Schipanski ME, Barbercheck M, Douglas MR, et al. 2014. A framework for evaluating ecosystem services provided by cover crops in agroecosystems. *Agr Syst* **125**: 12–22.

Shackelford G, Steward PR, Benton TG, et al. 2013. Comparison of pollinators and natural enemies: a meta-analysis of landscape and local effects on abundance and richness in crops. *Biol Rev* **88**: 1002–21.

Smart MD, Pettis JS, Euliss N, and Spivak MS. 2016. Land use in the Northern Great Plains region of the US influences the survival
and productivity of honey bee colonies. *Agr Ecosyst Environ* **230**: 139–49.

Snyder WE and Wise DH. 2001. Contrasting trophic cascades generated by a community of generalist predators. *Ecology* **82**: 1571–83.

Sponsler DB, Grozinger CM, Hitaj C, et al. 2019. Pesticides and pollinators: a socioecological synthesis. *Sci Total Environ* **662**: 1012–27.

Stanley DA, Garratt MPD, Wickens JB, et al. 2015. Neonicotinoid pesticide exposure impairs crop pollination services provided by bumblebees. *Nature* **528**: 548–50.

Stenberg JA. 2017. A conceptual framework for integrated pest management. *Trends Plant Sci* **22**: 759–69.

Stern VM, Smith RF, Van den Bosch R, and Hagen KS. 1959. The integration of chemical and biological control of the spotted alfalfa aphid: the integrated control concept. *Hilgardia* **29**: 81–101.

Tamburini G, Bommarco R, Kleijn D, et al. 2019. Pollination contribution to crop yield is often context-dependent: a review of experimental evidence. *Agr Ecosyst Environ* **280**: 16–23.

Thies C, Roschewitz I, and Tscharntke T. 2005. The landscape context of cereal aphid–parasitoid interactions. *P Roy Soc B-Biol Sci* **272**: 203–10.

Tschumi M, Albrecht M, Entling MH, and Jacot K. 2015. High effectiveness of tailored flower strips in reducing pests and crop plant damage. *P Roy Soc B-Biol Sci* **282**: 20151369.

van Lenteren JC, Bolckmans K, Köhl J, et al. 2018. Biological control using invertebrates and microorganisms: plenty of new opportunities. *BioControl* **63**: 39–59.

Westerkamp C and Gottsberger G. 2000. Diversity pays in crop pollination. *Crop Sci* **40**: 1209–22.

Zalucki MP, Adamson D, and Furlong MJ. 2009. The future of IPM: whither or wither? *Aust J Entomol* **48**: 85–96.

Zotti M, dos Santos EA, Cagliari D, et al. 2018. RNA interference technology in crop protection against arthropod pests, pathogens and nematodes. *Pest Manag Sci* **74**: 1239–50.

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### Bleaching in mangrove corals

Roughly half of coral species inhabiting Caribbean reefs also inhabit mangroves. Two alternative hypotheses suggest mangroves could promote coral survival under climate change: mangroves may serve as an “ecological refuge” for corals from heat extremes, or variable mangrove environments may select for resilience in corals to future perturbations (*Biogeosciences* 2014; doi.org/10.5194/bg-11-4321-2014). Both hypotheses presume different conditions in mangroves versus reefs and imply mangrove corals experience less heat-induced bleaching than reef conspecifics.

Observations made during longitudinal monitoring of corals inhabiting mangrove prop roots in Belize (*Front Mar Sci* 2020; doi.org/10.3389/fmars.2020.00377) suggest (1) bleaching is rarer in mangrove corals than in reef corals, and (2) bleaching in mangroves and bleaching in reefs may be driven by different environmental stressors. During four of five annual field seasons, we observed only one bleached colony among hundreds of mangrove corals, even as bleaching of the same species was widespread on nearby reefs during two of those field seasons. However, in one of the five field seasons, multiple coral species (such as *Millepora alcicornis*, *Porites astreoides*, and *Favia fragum*) inhabiting mangrove roots were bleached, specifically the shallowest corals (< 20 cm deep). In this instance, we suspect bleaching resulted from a surface lens of cold, hyposaline water generated by a rain-producing cold front that enveloped the site for ~5 days. Corals located below this lens did not bleach.

If different stressors trigger bleaching in reef and mangrove habitats, coral species that occur in both habitats may be better able to survive fluctuating temperature extremes. Given the potential importance of mangroves for coral survival, a key question is why some coral species can exploit mangrove habitats while others cannot.