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REVIEW

Integrated Crop Pollination: Combining strategies to ensure stable and sustainable yields of pollination-dependent crops

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Abstract

Our growing human population will be increasingly dependent on bees and other pollinators that provide the essential delivery of pollen to crop flowers during bloom. Within the context of challenges to crop pollinators and crop production, farm managers require strategies that can reliably provide sufficient pollination to ensure maximum economic return from their pollinator-dependent crops. There are unexploited opportunities to increase yields by managing insect pollination, especially for crops that are dependent on insect pollination for fruit set. We introduce the concept of Integrated Crop Pollination as a unifying theme under which various strategies supporting crop pollination can be developed, coordinated, and delivered to growers and their advisors. We emphasize combining tactics that are appropriate for the crop's dependence on insect-mediated pollination, including the use of wild and managed bee species, and enhancing the farm environment for these insects through directed habitat management and pesticide stewardship. This should be done within the economic constraints of the specific farm situation, and so we highlight the need for flexible strategies that can help growers make economically-based ICP decisions using support tools that consider crop value, yield benefits from adoption of ICP components, and the cost of the practices. Finally, education and technology transfer programs will be essential for helping land managers decide on the most efficient way to apply ICP to their unique situations. Building on experiences in North America and beyond, we aim to provide a broad framework for how crop pollination can help secure future food production and support society's increasing demand for nutritious diets.

Keywords: Bee; Food; Sustainability; Crop; Biodiversity; Management

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Introduction

As production of crops requiring insect-mediated pollination increases globally, there is a greater demand for crop-pollinating bees (Aizen & Harder 2009). Bees pollinate most of the fruit, vegetable and nut crops that enrich the diets of a growing human population by providing essential nutrients that complement dietary staples (Eilers et al., 2011) and mitigate nutrient deficiencies (Chaplin-Kramer et al., 2014; Ellis, Myers, & Ricketts 2015). Given these trends, development of effective pollination strategies that employ appropriate bee species in efficient ways will be important. To help address this challenge, we introduce the concept of Integrated Crop Pollination. We discuss how it might be implemented to help ensure the long-term stability of crop pollination, which is an essential component of sustainable and profitable production of many of our most nutritious crops.

The western honey bee (*Apis mellifera* L., Hymenoptera: Apidae) is an effective pollinator of many crops (Delaplane & Mayer 2000), but they are not always the most effective, and there is increasing recognition of the contributions of unmanaged populations of native bees (Winfree, Gross, & Kremen 2011; Garibaldi et al., 2013) and other insects (Rader et al., 2016). A small number of bee species exhibit characteristics that lend them to management for use as crop pollinators (Torchio, 1990; Mader, Spivak, & Evans 2010), thereby offering alternatives for some crops or as complementary pollinators to honey bees. These different sources of insect-mediated pollination provide opportunities to integrate wild and managed pollinators to help ensure stable and sustainable crop pollination (Kevan, Clark, & Thomas 1990; Williams, Isaacs, Lonsdorf, Winfree, & Ricketts, in press). However, growers and land managers have access to limited information for making practical decisions on the most effective and efficient strategies to support wild and managed pollinators for their crop pollination needs. Additionally, these decisions must be made within the context of the local or regional farm system, its existing pollination system, pest management intensity, economic resources, and the available bee species that are practicable to align with and integrate into the crop production system. Given the complexity of crop pollination, decision-support systems are needed for growers and other land managers to help ensure reliable pollination for stable and profitable crop production.

Integrated Crop Pollination

As an organizing concept to structure the development and evaluation of efficient and flexible pollination strategies, we introduce the concept of Integrated Crop Pollination (ICP). We define ICP as: *The use of managed pollinator species in combination with farm management practices that support, augment, and protect pollinator populations to provide reliable and economical pollination of crops* (Fig. 1). This concept includes the expectation that no single strategy will be the best option for all locations where a crop is grown, due to variation in the level of pollinator dependence, the managed and wild bee populations, crop variety, local economics of production, horticultural practices and personal preference. The approach builds on a strong foundation of research and implementation, ensuring the delivery of practical options aligned for diverse farming contexts.

Lack of comparisons between pollination strategies using a return-on-investment analysis approach inhibits growers ability to consider the relative benefits of honey bees and complementary of alternative strategies. By embracing the diversity of tactics that can be applied to specific farm situations, ICP provides a framework to guide the designing, development, and testing of multiple pollination strategies, including correlating their benefit to farm revenues. In many ways this approach echoes the development of Integrated Pest Management (IPM) 50 years ago, which brought a formal, quantitative approach to the interactions between pests, crops, and farm revenues (Kogan, 1998). Here, we outline the key principles on which an ICP strategy can be developed, describe its primary components (Fig. 1), and discuss applied research needed to transition from concept to a useful structure for decision-making by managers of specialty crops.

Integration of pollinators on farms

Managing crop pollination from an ICP perspective includes the integration and diversification of pollinators and will require balancing the pros and cons of using a single managed bee species such as the honey bee, mixtures of managed species, and/or wild bee pollinators. Although non-bee pollinators can be important in some contexts (Rader et al., 2015), for the purposes of this review they are not considered. The ICP framework (Fig. 1) recognizes the essential role of honey bees as specialty crop pollinators. In some situations, increasing stocking density can be the most effective and economical option for achieving the desired pollination goals with the greatest return on investment. In others, combining honey bees with other pollinating insects can improve pollination (Brittain, Williams, Kremen, & Klein, 2013a) and may reduce the risk of poor yields caused by annual variability in pollinator activity. We assume that the context under which alternative pollinators are likely to be most effective and economically practical is dictated by a combination of factors including the landscape surrounding the farm, how the farm is managed, the reproductive biology and phenology of the crops, and the relative efficacy and cost of different managed bee species. Each farmer will have a specific set of pollination options available that can be selected and integrated into their farming practices to provide for their pollination needs (Fig. 2), and so we recognize the challenge of devel-