Received: 30 July 2019 | Accepted: 21 December 2019
DOI: 10.1111/1365-2664.13574

PRACTITIONER'S PERSPECTIVE

Journal of Applied Ecology BRITISH ECOLOGICAL SOCIETY

Crop pollination management needs flower-visitor monitoring and target values

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Funding information
Universidad Nacional de Río Negro, Grant/Award Number: PI 40-B-399 and PI 40-B-567; Fondo para la Investigación Científica y Tecnológica, Grant/Award Number: PICT 2015-2333; 2017–2018 Belmont Forum and BiodivERsA; AEI; NWO; ECCyT; NSF

Handling Editor: Sarah Diamond

Abstract

1. Despite the crucial importance of biotic pollination for many crops, land managers rarely monitor the levels of crop pollination needed to guide farming decisions.
2. The few existing pollination recommendations focus on a particular number of honeybee or bumblebee hives per crop area, but these guidelines do not accurately predict the actual pollination services that crops receive.
3. We argue that pollination management for pollinator-dependent crops should be based on direct measures of pollinator activity. We describe a protocol to quickly perform such a task by monitoring flower visitation rates.
4. We provide target values of visitation rates for crop yield maximization for several important crops by considering the number of visits per flower needed to ensure full ovule fertilization. If visitation rates are well below or above these target values, corrective measures should be taken.
5. Detailed additional data on visitation rates for different species, morpho-species, or groups of species and/or flower-visitor richness can improve pollination estimates.
6. *Synthesis and applications*. We present target values of visitation rates for some globally important pollinator-dependent crops and provide guidance on why monitoring the number and diversity of pollinators is important, and how this information can be used for decision-making. The implementation of flower monitoring programmes will improve management in many aspects, including enhanced quality and quantity of crop yield and a more limited spillover of managed (often exotic) pollinators from crop areas into native habitats, reducing their many potential negative impacts.

KEYWORDS
agricultural management, bees, biodiversity, crop yield, decision-making, ecological intensification, farming practices, pollination

1 | FARMING NEEDS TO MONITOR CROP FLOWER VISITATION

Farming practices commonly involve the monitoring of soil nutrients to quantify the amount of fertilizer needed, or the use of traps to assess when pest abundances exceed certain economic damage thresholds. However, even though biotic pollination is important for many crops (Potts et al., 2016), it is rarely monitored. Over the past several decades, the number of studies on crop pollination has increased rapidly (Potts et al., 2016), but unfortunately, this large body of research has not been translated into specific management guidelines. The development of such guidelines to monitor flower visitors

TABLE 1 Studies found to estimate the number of visits per flower needed to ensure full ovule fertilization

Crop	Breeding system[a]	Visits per flower for full fertilization	Days of flower receptivity	Target values (visits in 100 flowers during 1 hr)	Main pollinators	References for visits per flower for full fertilization	References for days of flower receptivity
Apple	Hermaphroditic	10	3	55	Honeybees, solitary bees	Vicens and Bosch (2000)	Losada and Herrero (2013)
Blueberry	Hermaphroditic	>10	2	160	Honeybees	Danka, Lang, and Gupton (1993)	Ngugi, Scherm, and Lehman (2002); Young and Sherman (1978)
Blueberry	Hermaphroditic	1–10	2	8–80	Bumblebees, honeybees, solitary bees	Javorek, Mackenzie, and Vander Kloet (2002)	Ngugi et al. (2002); Young and Sherman (1978)
Cranberry	Hermaphroditic	2–3	4	10	Bumblebees, honeybees, solitary bees	Cane and Schiffhauer (2003)	Kirk and Isaacs (2012); Moore (1964)
Raspberry	Hermaphroditic	10	3	55	Bumblebees, honeybees	Sáez, Morales, Morales, Harder, and Aizen (2018)	Hiregoudar Manju and Bundela (2019)
Strawberry	Hermaphroditic	4	4	16	Honeybees	Chagnon, Gingras, and De Oliveira (1989)	Yoshida, Goto, Chujo, and Fujime (1991)
Strawberry	Hermaphroditic	1	4	4	Honeybees, solitary bees, syrphid flies	Albano, Salvado, Duarte, Mexia, and Borges (2009)	Yoshida et al. (1991)
Sweet pepper	Hermaphroditic	>2	5	13	Bumblebees	Roldán Serrano and Guerra-Sanz (2006)	Kaul (1991)
Tomato	Hermaphroditic	3	5	10	Bumblebees	Morandin, Laverty, and Kevan (2001)	Kaul (1991)
Cucumber	Monoecious	18	3	100	Bumblebees, honeybees	Stanghellini, Ambrose, and Schulthcis (1998)	Le Deunff, Sauton, and Dumas (1993)
Cucumber	Monoecious	>5	3	55	Honeybees	Gingras, Gingras, and De Oliveira (1999)	Le Deunff et al. (1993)
Pumpkin	Monoecious	>8	3	88	Bumblebees, honeybees	Artz and Nault (2011)	Nepi and Pacini (1993)
Pumpkin	Monoecious	1–50	3	5–275	Bumblebees, honeybees, solitary bees	Pfister et al. (2017)	Nepi and Pacini (1993)
Watermelon	Monoecious	8	2	64	Honeybees	Adlerz (1966)	Kwon, Jaskani, Ko, and Cho (2005)
Watermelon	Monoecious	12	2	96	Bumblebees, honeybees	Stanghellini et al. (1998)	Kwon et al. (2005)
Kiwi	Dioecious	>5	4	41	Honeybees	Goodwin, McBrydie, and Taylor (2013)	González, Coque, and Herrero (1995)
Kiwi	Dioecious	20	4	83	Honeybees	Sáez, Negri, Viel, and Aizen (2019)	González et al. (1995)

Note: Considering that these visits should occur while the flowers are receptive, and assuming 6 hr of daily pollinator activity, we estimated optimal flower visitation rates for highest crop yield (target values) to guide pollinator management.

[a]Hermaphroditic crops have both female and male parts on the same flowers, monoecious crops have separate female and male flowers on the same individuals, and dioecious crops have distinct female and male individual organisms.

and determine visitation rates that, from a pollination perspective, maximize crop yield (tonnes per hectare) would be useful for farmers worldwide, increasing both their income and also pollinator health.

Where they are applied, most pollination practices focus on managing the number of hives of eusocial species such as honeybees, bumblebees or stingless bees, and, rarely, abundances of a few solitary bees (Garibaldi, Requier, Rollin, & Andersson, 2017; Ullmann et al., 2017). In fact, most pollination handbooks are based on recommendations of a particular number of honeybee hives per crop-cultivated area (e.g. Free, 1993). However, these guidelines do not accurately predict the actual pollination services crop plants receive (Rollin & Garibaldi, 2019). A fixed number of hives can translate into contrasting visitation rates to crop flowers because hives can have different population sizes or be located at varying distances (and configurations) to crop flowers. Furthermore, visitation to crop flowers also depends on the intrinsic features of the crop itself and the external context such as the attractiveness of neighbouring vegetation and interactions with wild pollinators (Rollin & Garibaldi, 2019). We argue that pollination management for pollinator-dependent crops should be based on direct measures of pollinator activity and that this can be accomplished by monitoring flower visitation rates.

Crop pollination studies generally use one of two methods to assess the effect of flower visitors on crop yield: transect counts or visitation rates (Garibaldi et al., 2013; Vaissière, Freitas, & Gemmill-Herren, 2011). Standardized transect counts can give a good idea of insect activity, and they are a commonly used method to compare insect densities across crop fields (O'Connor et al., 2019). However, transect counts might introduce noise because illegitimate flower visits and non-visiting insects may also be recorded, and in some studies they do not register the number of flowers, nor do they quantify the between-flower pollinator movement, which are essential for cross-pollination. A more direct measure is the observations of visits to crop flowers (i.e. visitation rates). For this method, an observer

BOX 1. Protocol for a quick assessment of flower visitation rates in the field to determine a proxy of the level of crop pollination

What to measure?

Visits to flowers from bees, like honeybees or bumblebees; flies; beetles; or any flying insect contacting the reproductive part of the flowers (anthers or stigma). Do not count insects that are not legitimately visiting the flowers, such as those that only perch on the petals.

How?

Count the number of visits to open flowers (or groups of flowers for some crops, see more details in Vaissière et al., 2011) for a standard amount of time, at least 5 min. Repeat this observation at different times during the same day for plants that are minimally 10 m apart. The total observation time should be at least 20 min, for example, resulting from two measurements of 5 min in the morning and another two in the afternoon (Fijen & Kleijn, 2017). Then, express the overall number of visits per 100 flowers during 1 hr.

Where?

The centre of the crop field, where pollinator deficits are expected to be the highest (Garibaldi et al., 2011).

When?

Visitation rates should be measured at least three times: when the crop has approximately 25%, 50% and 75% of its flowers open. Field observations should be performed in the absence of rain or strong winds (see more details in Vaissière et al., 2011).

Decision-making

Considering the number of visits per flower needed to ensure full ovule fertilization, the duration of flower receptivity and assuming 6 hr of daily pollinator activity, we provide approximate values of visitation rates for highest possible crop yield (Table 1). If visitation rates are well below or above these target values, corrective measures should be taken (see main text). However, note that such values may change according to crop variety and environmental conditions.

Flower-visitor richness

In addition, visitation rates can be registered for different species, morpho-species or groups of species. Studies suggest that higher flower-visitor richness is always better for crop pollination (i.e. linear relation; Garibaldi et al., 2016). This means that, though there are no target values for pollinator richness, monitoring richness and trying to maximize it is good practice.

documents each legitimate visit (i.e. contacting reproductive structures) to a specified flower (or group of flowers) during a fixed observation period, which can vary depending on the crop, and repeats this observation several times for different flowers to ensure a representative average (Fijen & Kleijn, 2017; O'Connor et al., 2019). The advantage of this method is that it directly relates to scientific studies that estimate how many visits a single flower requires to fully fertilize its receptive ovules (i.e. perfect fruit or seed set; Table 1). Hence, the farmer can relate visitation rates to actual levels of pollination and subsequent fruit or seed set. In addition, there are ongoing software developments to measure visitation rates in flowers automatically, such as automated photographic and video setups or electrical sensors, facilitating the adoption of pollination measurements in crops in real time. Sometimes transect counts and visitation rates are strongly correlated (Figure S1). In these cases, land managers might choose to do transect counts as they are faster to perform at the field level, and use regression models (with the help of an agricultural extension worker, guided software or custom cell phone applications) to estimate visitation rates (see examples in Figure S1). The exact circumstances necessary for the relationship between numbers of individuals and visitation rates to hold remain elusive, however, and visitation rates are consequently a preferable method.

Once flower visitation rates are obtained (Box 1), they need to be compared with target values to assess which interventions are required. Fortunately, a wealth of studies on crop–pollinator

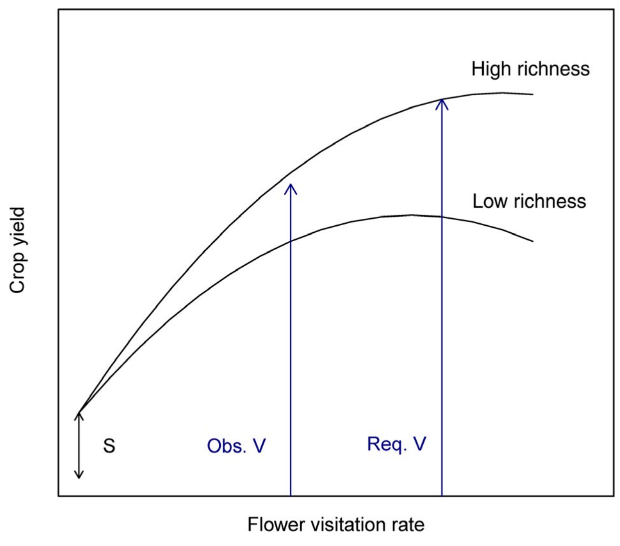

FIGURE 1 Example of a simple predictive model using knowledge on the crop characteristics that can be tailored to the crop variety (e.g. S, production without pollinators), required visitation rates (Req. V; extracted from Table 1) and observed visitation rates (Obs. V; measured by the farmer). In general, crop yield increases with flower visitation at different rates according to pollinator richness (Garibaldi et al., 2013, 2016). Greater pollinator richness also increases potential crop yield (Garibaldi et al., 2013, 2016). Flower visitation rates should be monitored for decision-making according to the protocol described in Box 1, while target values for crop species with different breeding systems are provided in Table 1

interactions are available for developing monitoring guidelines. Here, we present target values of visitation rates for some globally important pollinator-dependent crops (Table 1). Then, we provide guidance on why monitoring the number and diversity of pollinators is important, and how best this information can be used for decision-making. A critical next step is to convert the data provided here into an openly accessible database of flower visitation target values. Furthermore, as it has already happened with integrated pest management, simple predictive models using these type of data will soon be developed and offered by extensionists, enterprises and agricultural cooperatives to farmers, which will facilitate the interpretation of the data and improve management (Figure 1).

2 | HOW MANY POLLINATOR INDIVIDUALS ARE REQUIRED?

It is generally assumed that more pollinators on flowers are always better, because more pollen grains are deposited on the stigmas (Vázquez, Morris, & Jordano, 2005). However, there is a nonlinear relation of visitation rates with crop yield (Figure 1), where, under high visitation rates, the benefit of having more pollinators is lower, or even reversed, becoming detrimental (Aizen et al., 2014; Rollin & Garibaldi, 2019; Sáez et al., 2018). Therefore, a key issue is estimating the optimal number of pollinators required to maximize ovule fertilization and yield for each crop (Figure 1). This optimal number will depend on the crop type, pollinator identity and environmental conditions (Table 1). For example, a crop's breeding or sexual system can be classified as hermaphroditic, monoecious or dioecious, reflecting increased pollinator dependency and the required visitation rate for assurance of optimal pollination (Table 1; Rollin & Garibaldi, 2019).

While some studies show that crop pollination levels appear to be optimal in real-world systems (Pfister, Eckerter, Schirmel, Cresswell, & Entling, 2017), the greater weight of evidence suggests that current pollination levels are usually suboptimal, that is in the linear part of the curve (Figure 1). A synthesis of 344 fields from 33 pollinator-dependent crop systems in small and large farms from Africa, Asia and Latin America found a linear relation between crop yield and flower-visitor density, showing that the highest levels of flower-visitor density observed around the world are still at non-saturated values (Garibaldi et al., 2016). As an illustration, these flower-visitor density values can be translated into expected visitation rates, and, when doing so (Figure S1), such values remain lower than most of the optimal visitation rates found in Table 1. Another example is a recent meta-analysis of the influence of honeybees on crop fruit or seed set (Rollin & Garibaldi, 2019), which found optimal values of flower-visitor density that align well with those of Table 1. Although there is high variation in the optimal values for visitation rates across biotic and abiotic conditions, studies measuring visitation rates or flower-visitor density across crop fields are in agreement with the general values found by those measuring the number of visits per flower needed to ensure full ovule fertilization (Table 1).

3 | HOW MANY SPECIES OF POLLINATORS ARE REQUIRED?

Several studies have shown that crop yield increases linearly with pollinator richness (no. of species), although the ranges of species richness are sometimes low in crop fields (e.g. 0–11 species in Garibaldi et al., 2016). The enhancement of habitats for wild pollinators is the main strategy to increase flower-visitor richness, as few pollinator species can be managed at present and the majority of species in a crop field are wild pollinators (Garibaldi et al., 2017). It is important to note that highly abundant, single pollinator species cannot replace the beneficial effects of pollinator richness, so species richness effects are complementary to those from abundance (Fijen et al., 2018; Garibaldi et al., 2013, 2016). This could be due to several, non-exclusive mechanisms (Tscharntke, Klein, Kruess, Steffan-Dewenter, & Thies, 2005), including that different pollinator species handle flowers differently, visit flowers at different times of the day (Fründ, Dormann, Holzschuh, & Tscharntke, 2013; Hoehn, Tscharntke, Tylianakis, & Steffan-Dewenter, 2008), change the behaviour of other pollinator species (Brittain, Williams, Kremen, & Klein, 2013; Carvalheiro et al., 2011) or increase the chance that an effective pollinator is present in the community (Cardinale et al., 2006; Schleuning, Fründ, & García, 2015). As a general rule of thumb, higher species richness of crop pollinators is likely to increase crop yield, so land managers should strive to increase and improve wild pollinator habitat.

4 | WHAT TO DO WHEN POLLINATOR NUMBERS ARE SUB OR SUPRA-OPTIMAL?

When the monitoring of flower visitation rates reveals that pollinator levels are sub or supra-optimal for crop yield (Figure 1), a farmer can take both short- and long-term actions to improve pollination. Short-term decisions usually involve increasing or decreasing the abundance of managed pollinators (e.g. through managing the number of honeybee or bumblebee hives) and changes in pesticide management (Ullmann et al., 2017). Long-term decisions usually involve landscape planning and provisioning diverse floral and nesting resources throughout the growing season and beyond, to benefit species which typically only partially overlap with crop bloom periods (Garibaldi et al., 2014). This can be done through, for example, the enhancement and conservation of natural and semi-natural habitats, promotion of habitat diversity and the planting of floral strips and hedgerows (Garibaldi et al., 2014). In practice, some farmers mow grasslands or road verges to remove wild flowers because they are perceived as competition for mass-flowering crops. However, many studies find that removing co-flowering wild flowers does not increase crop pollination and has the negative side effect of harming the less-prevalent species (Fijen, Scheper, Boekelo, Raemakers, & Kleijn, 2019; Garibaldi et al., 2014). It is clear that there is no one-size-fits-all solution to sub or supra-optimal pollination values. Instead, optimal crop pollination needs integrated management of effective, managed pollinator species and the enhancement of (semi-) natural habitats for increasing wild pollinator richness (Garibaldi et al., 2013, 2017). The effectiveness of such measures should be regularly monitored with the protocol described here.

5 | WHERE TO GO FROM HERE?

Scientific knowledge, by definition, will always be incomplete. Research during the next decades will provide, among many other advances, more precise measures of optimal visitation rates and flower-visitor richness for different crop types across environments (Sáez et al., 2018). Although we only provide approximate numbers of visitation rates for crops with contrasting breeding systems, using such numbers through the implementation of flower monitoring programmes will improve management in many aspects, including enhanced quality and quantity of crop yield. In addition, given that in some places pollinators are managed at densities that are higher than optimal, we expect these guidelines to result in a more limited spillover (Garibaldi et al., 2017) of managed (often exotic) pollinators from crop areas into natural or semi-natural areas, reducing their many potential negative impacts (Vanbergen, Espíndola, & Aizen, 2018).

ACKNOWLEDGEMENTS

We appreciate funding from Agencia Nacional de Promoción Científica y Tecnológica (PICT 2015-2333), Universidad Nacional de Río Negro (PI 40-B-399, PI 40-B-567), and the 2017–2018 Belmont Forum and BiodivERsA joint call for research proposals (under the BiodivScen ERA-Net COFUND programme and with the funding organizations AEI, NWO, ECCyT and NSF). This manuscript was reviewed by practitioners from the agricultural sector. Adrián González Chaves, Agustín Bilbao, Barbara Gemmill-Herren, Dulce Gómez Carella, José R. Micheloud, Juan Ignacio Aguero, Michael Orr, Nancy García and Pablo Hünicken provided great suggestions on previous versions of the manuscript.

AUTHORS' CONTRIBUTIONS

L.A.G., A.S., M.A.A., T.F. and I.B. frequently interacted, discussed ideas and jointly wrote the manuscript.

DATA AVAILABILITY STATEMENT

Data have not been archived because this article does not contain data.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Garibaldi LA, Sáez A, Aizen MA, Fijen T, Bartomeus I. Crop pollination management needs flower-visitor monitoring and target values. *J Appl Ecol*. 2020;00:1–7. https://doi.org/10.1111/1365-2664.13574